DESY • BSM faces LHC run-2 realities • 16 Sep 2016

Top-quark samples as not just background

Yevgeny Kats
CERN

Top-quark samples

... as calibrators of *s*, *c*, *b* polarization measurements

arXiv:1505.02771 [JHEP 1511, 067 (2015)] with Galanti, Giammanco, Grossman, Stamou, Zupan

arXiv:1505.06731 [PRD 92, 071503 (2015)]

... as a hiding place for new physics

arXiv:1602.08819 [JHEP 1605 (2016) 092] with Strassler

work in progress with McCullough, Perez, Soreq, Thaler

work in progress with Giammanco, Schlaffer, Shlomi → **talk by Schlaffer**

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... as a hiding place for new kind of top partners

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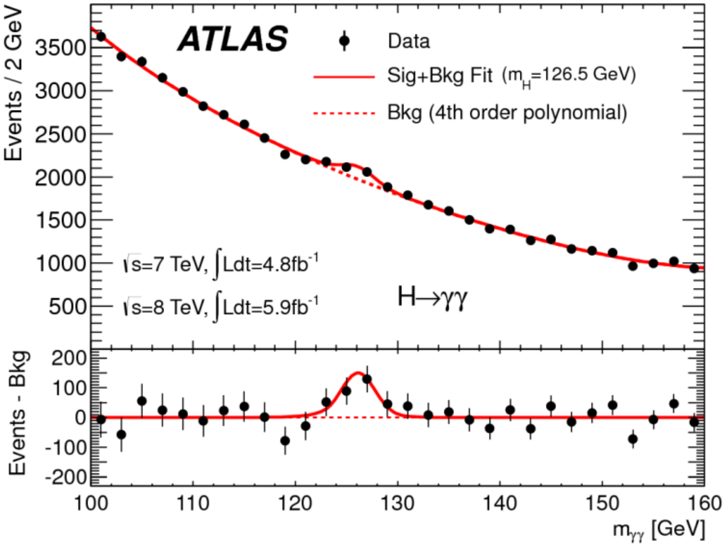
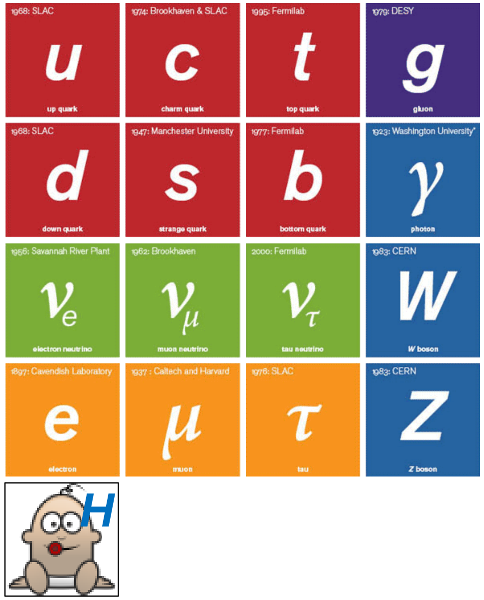
Part 1

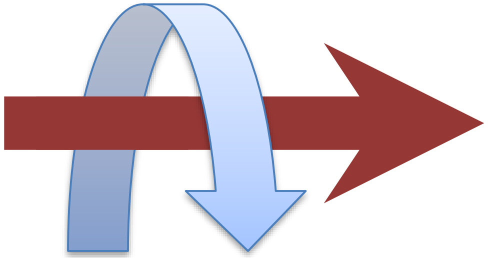
Top-quark samples as calibrators of s, c, b polarization measurements

Motivation

Commonly, information about new physics is encoded in the produced Standard Model particles.







Particle carries information in its **momentum** and **spin**.

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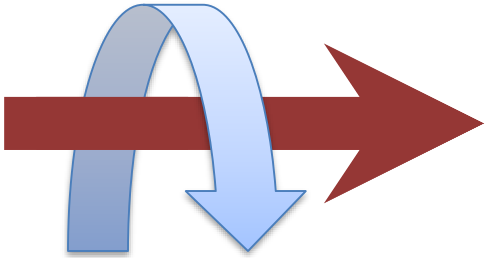
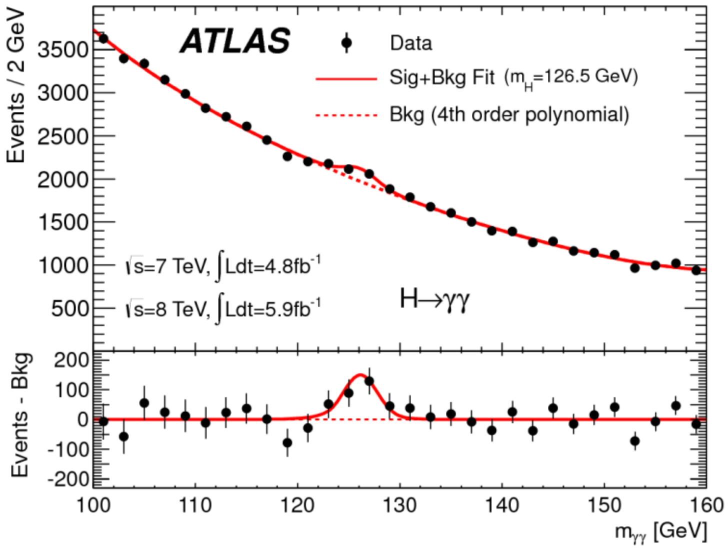




Particle carries information in its **momentum** and **spin**.

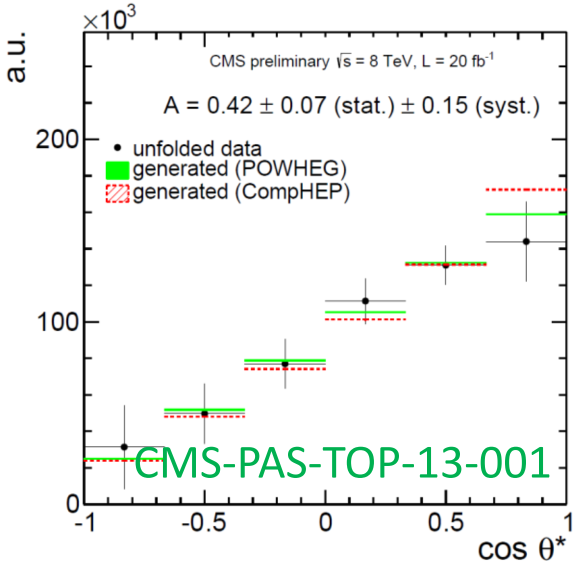
For **quarks**, momentum is easily reconstructed.

Is it possible to measure also their spin state (polarization)?

Motivation

Top quark polarization measurements are now standard.

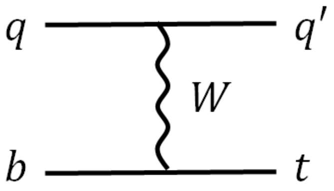
single top production



CMS-PAS-TOP-13-001

$$P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.)$$

EW process → polarized



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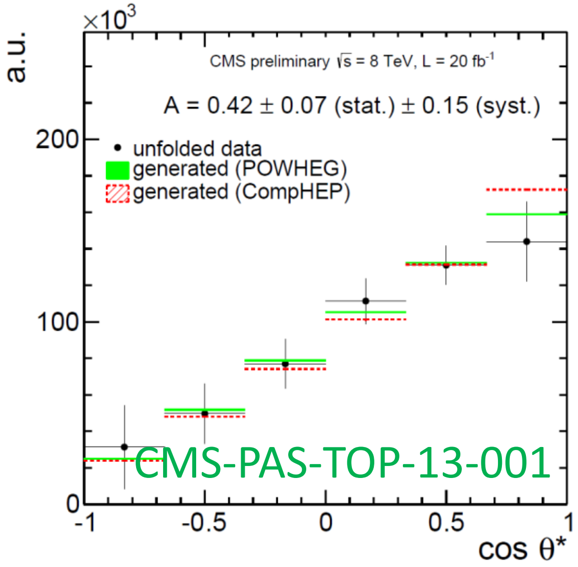
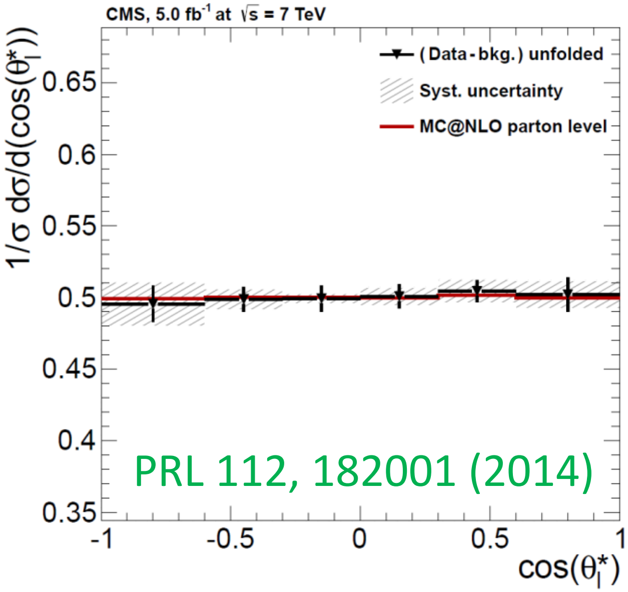


CMS-PAS-TOP-13-001

$$P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.)$$

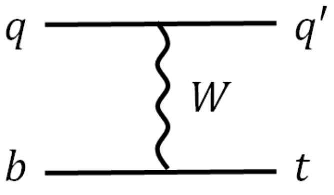
top pair production

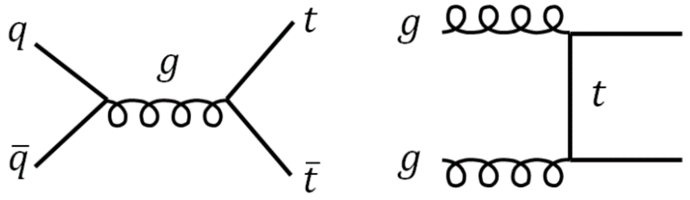


PRL 112, 182001 (2014)

EW process → polarized

QCD process → unpolarized





etc.

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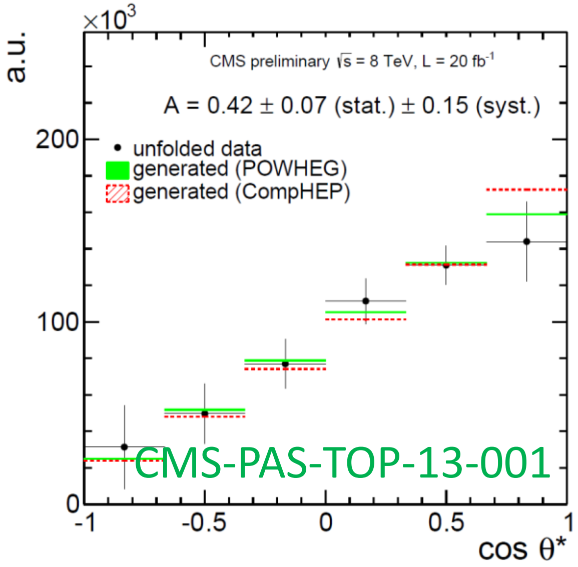

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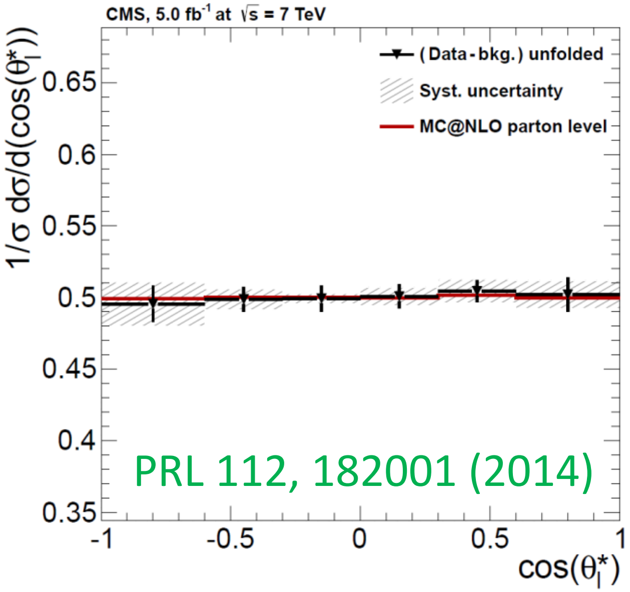

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Polarization of tops from **new physics** processes will teach us about their production mechanism!

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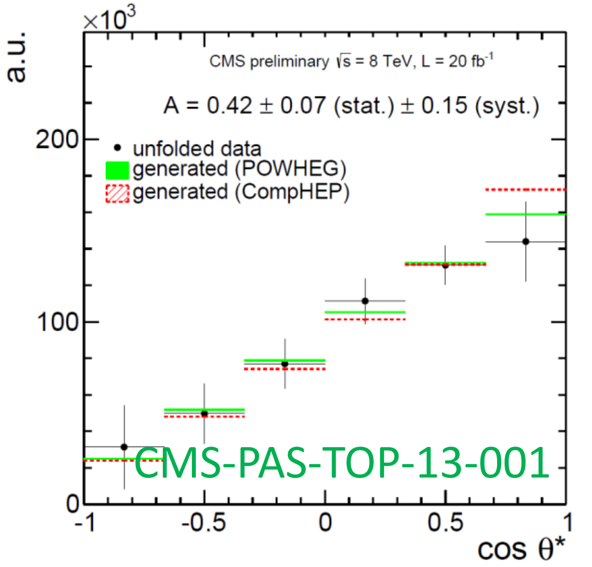

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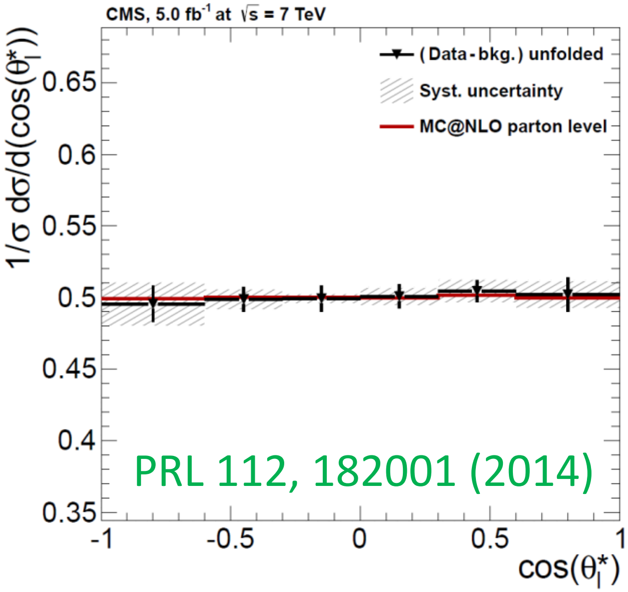

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Polarization of tops from **new physics** processes

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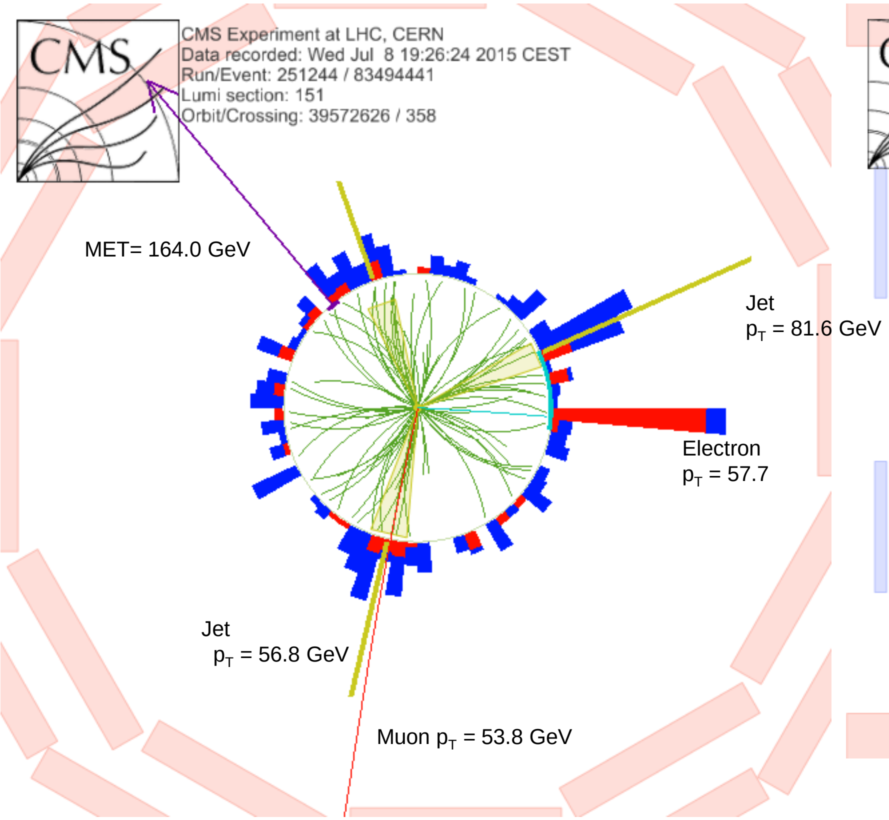
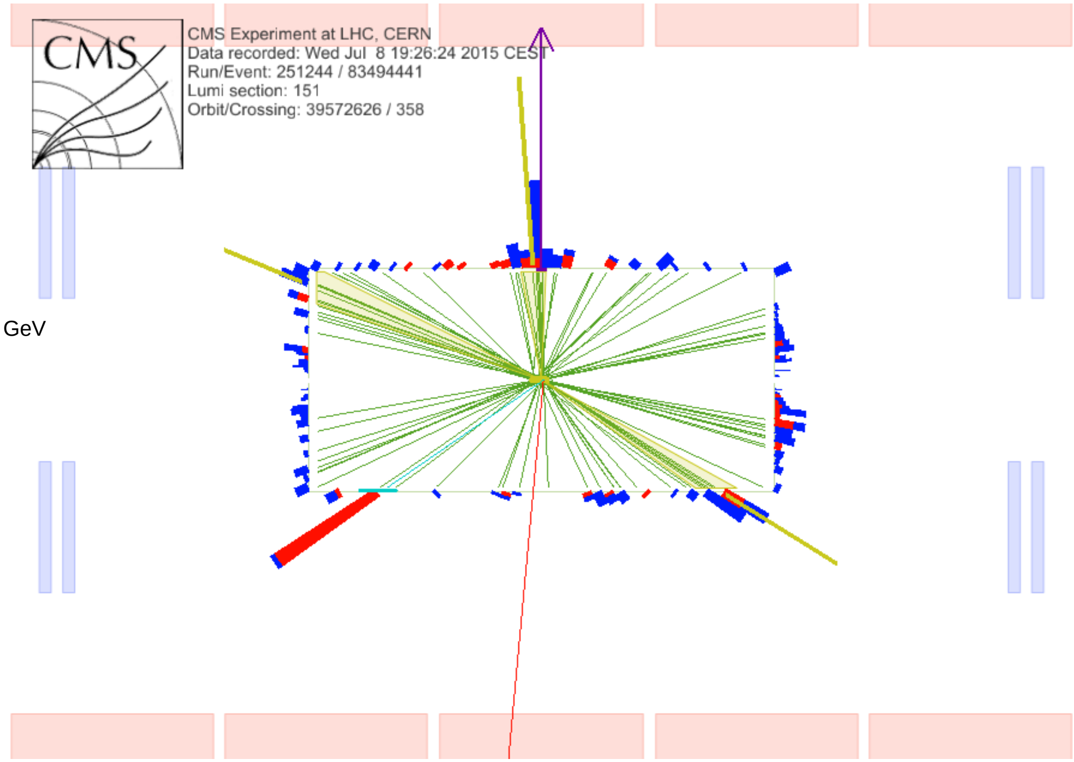
Can we do analogous measurements for the **other quarks**?

Motivation





Quarks produce jets of hadrons.

Quark’s **momentum** reconstructed from tracks, calorimeter deposits.

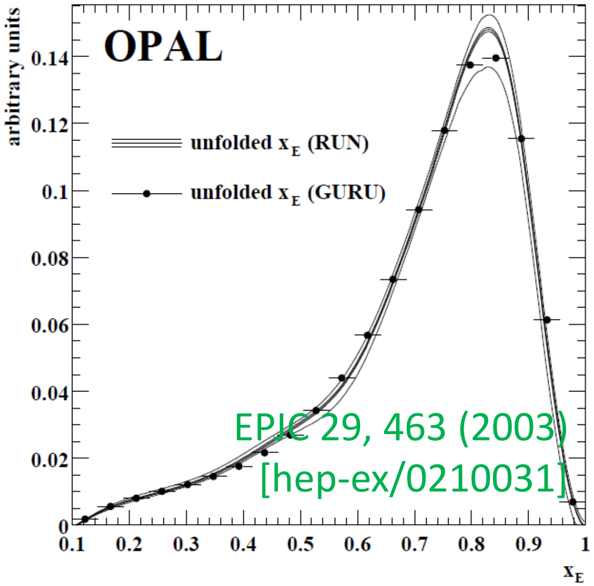
How can one reconstruct quark’s **spin state (polarization)**?

Heavy quarks (b, c)

For heavy quarks, $m_q \gg \Lambda_{\text{QCD}}$

- The jet contains a **very energetic** heavy-flavored hadron.
- When it is a **baryon**, $\mathcal{O}(1)$ fraction of the polarization is expected to be retained.

Falk and Peskin
PRD 49, 3320 (1994)
[hep-ph/9308241]



EPJC 29, 463 (2003)
[hep-ex/0210031]

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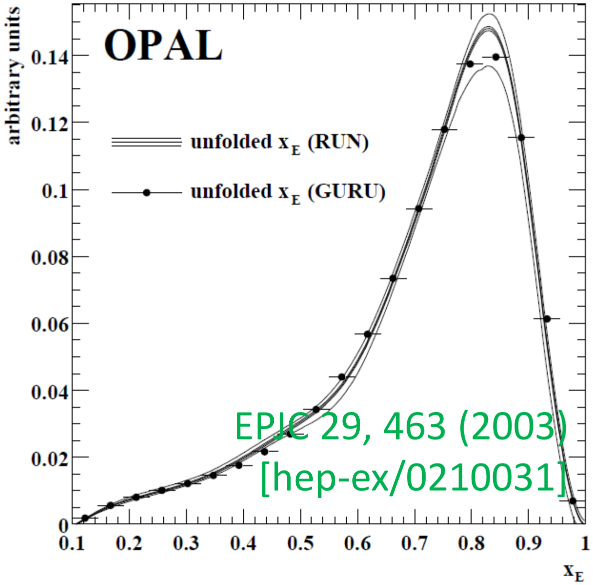

EPJC 29, 463 (2003)
[hep-ex/0210031]

Evidence observed at **LEP** via Λ_b ($\approx bud$) baryons in $Z \to b\bar{b}$.

$\mathcal{P}(\Lambda_b) = -0.23^{+0.24}_{-0.20}{}^{+0.08}_{-0.07}$ (ALEPH) PLB 365, 437 (1996)

$\mathcal{P}(\Lambda_b) = -0.49^{+0.32}_{-0.30} \pm 0.17$ (DELPHI) PLB 474, 205 (2000)

$\mathcal{P}(\Lambda_b) = -0.56^{+0.20}_{-0.13} \pm 0.09$ (OPAL) PLB 444, 539 (1998) [hep-ex/9808006]

s quark

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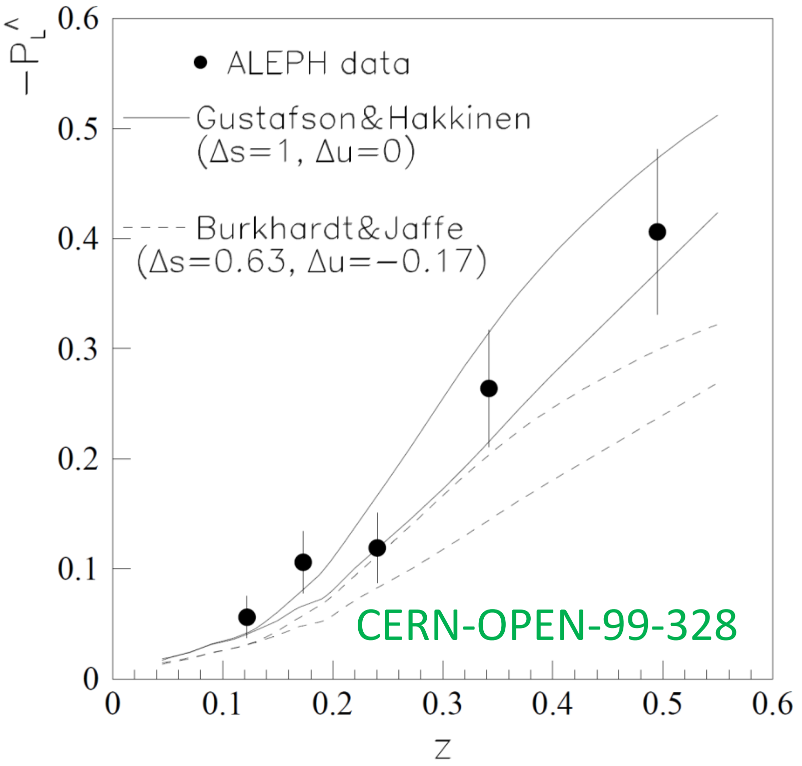
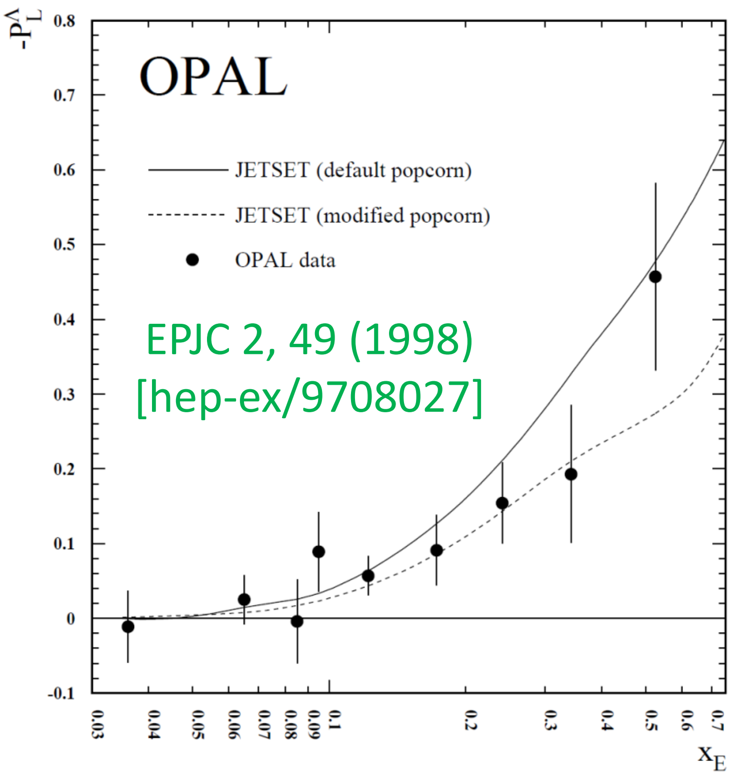


CERN-OPEN-99-328



EPJC 2, 49 (1998)
[hep-ex/9708027]

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  For $z > 0.3$:

  $\mathcal{P}(\Lambda) = -0.31 \pm 0.05$ **ALEPH**, CERN-OPEN-99-328

  $\mathcal{P}(\Lambda) = -0.33 \pm 0.08$ **OPAL**, EPJC 2, 49 (1998) [hep-ex/9708027]

  Contributions from all quark flavors are included.

  For strange quarks only (non-negligible modeling uncertainty):

  $$-0.65 \lesssim \mathcal{P}(\Lambda) \lesssim -0.49$$

  Sizable polarization retention!

Opportunity in ATLAS/CMS $t\bar{t}$ samples

- $t \to W^+ b$ produces polarized b quarks.
  - $\hookrightarrow c\bar{s}$ produces polarized c, s quarks.

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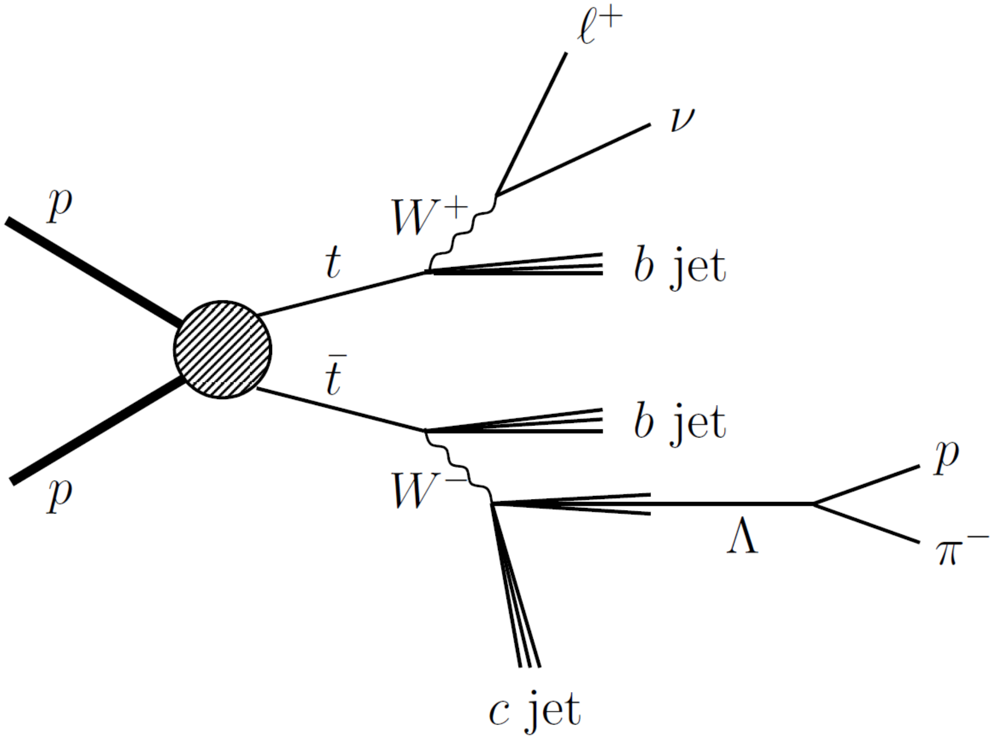
- Interplay with HQET, models of QCD, lattice QCD,
  LEP, LHCb, polarized DIS, polarized pp collisions.

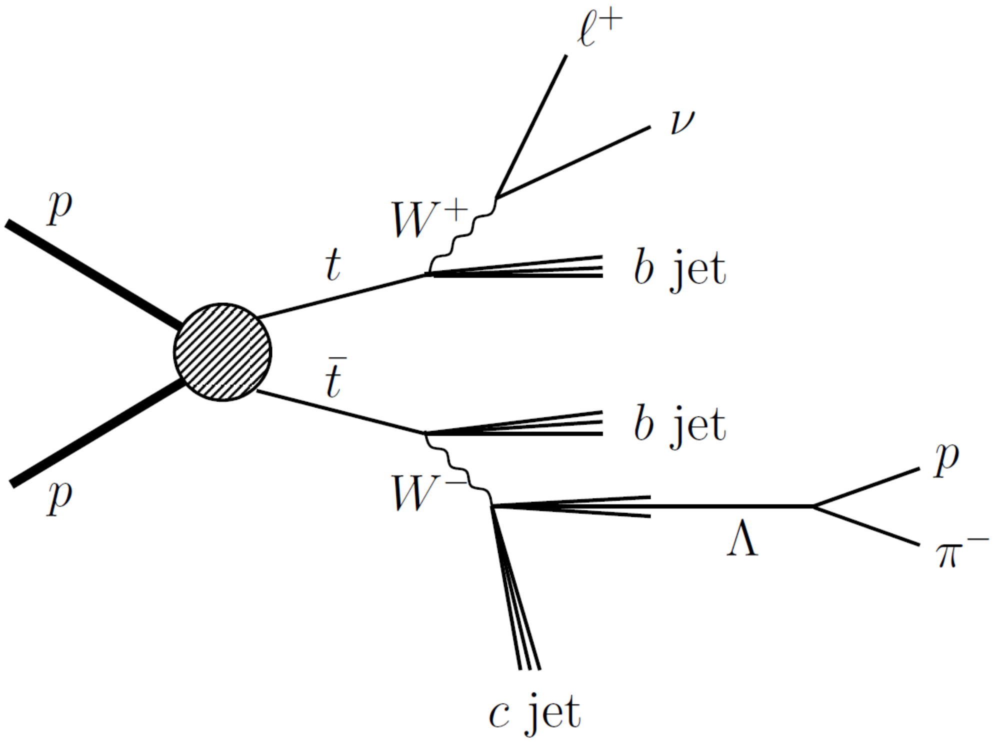
Measurement of s polarization in $t\bar{t}$



Main steps:

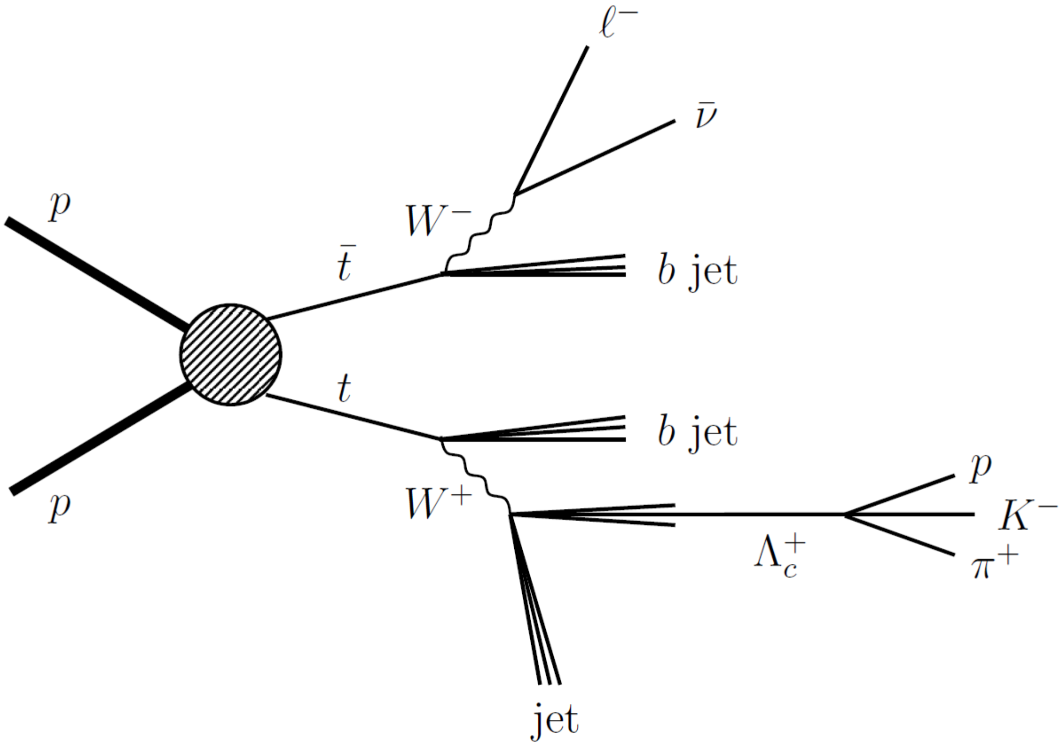
- Typical single-lepton $t\bar{t}$ selection
- Typical kinematic reconstruction and global event interpretation
- Charm tagging
- Λ reconstruction and polarization measurement

Measurement of s polarization in $t\bar{t}$



Statistical precision of roughly 16% possible at ATLAS/CMS in Run 2 (with 100/fb of data)

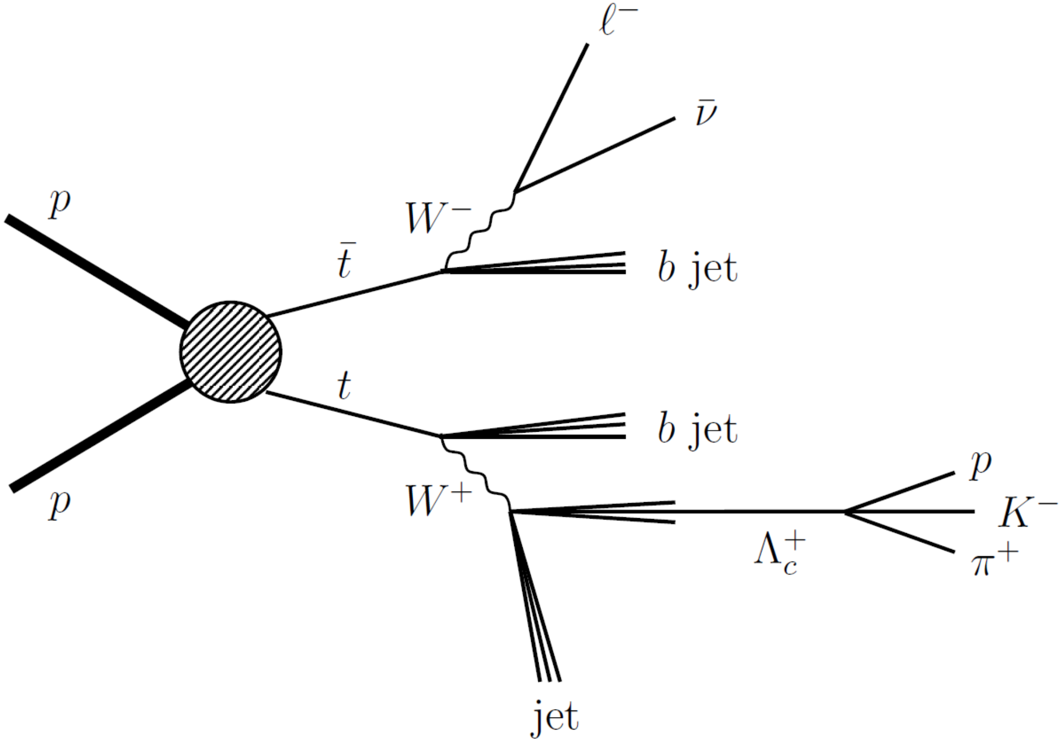
Measurement of c polarization in $t\bar{t}$



Main steps:

- Typical single-lepton $t\bar{t}$ selection
- Typical kinematic reconstruction and global event interpretation
- Λ_c reconstruction and polarization measurement

Measurement of c polarization in $t\bar{t}$

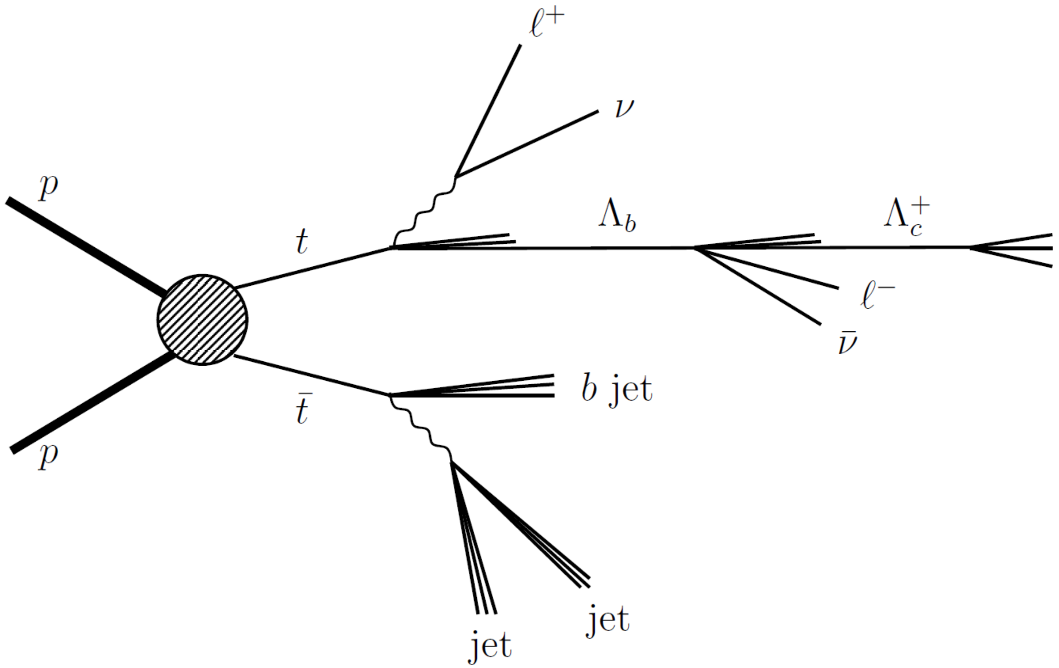


Statistical precision of order 10% possible at ATLAS/CMS in Run 2 (with 100/fb of data)

$\alpha_i r_L = 0.6$

Selection	Expected events	Purity (example)	$\Delta\mathcal{A}_{FB}/\mathcal{A}_{FB}$
Baseline	$1.7\times10^6\ t\bar{t} + \mathcal{O}(10^5)$ bkg		
$\Lambda_c^+ \to pK^-\pi^+$	$810\times(\epsilon_{\Lambda_c}/25\%)$	20% 100%	26% 11%

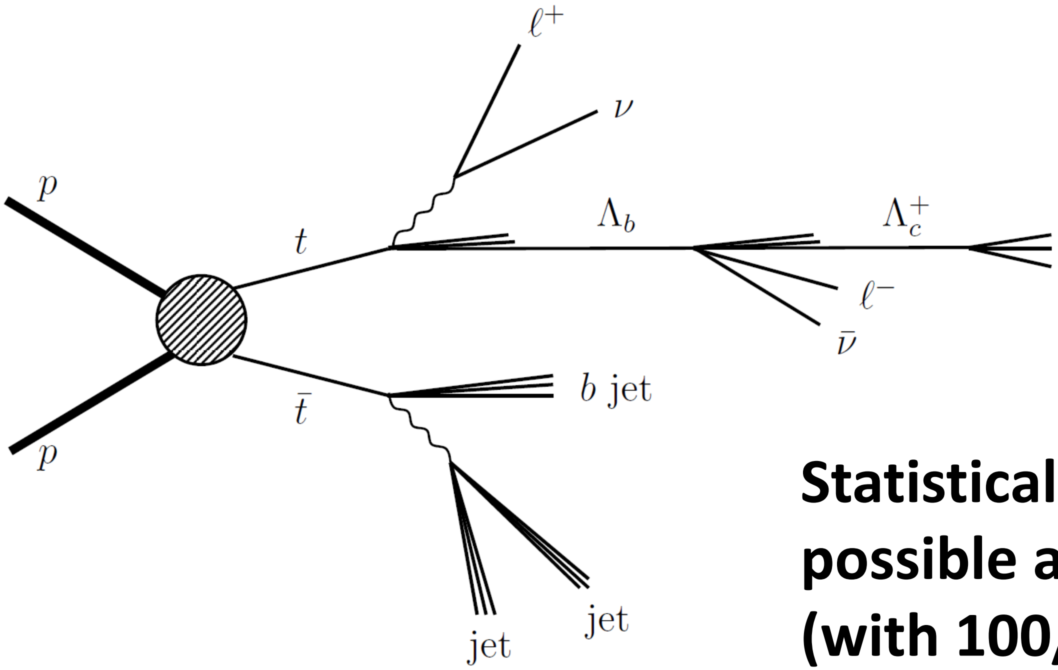
Measurement of b polarization in $t\bar{t}$



Main steps:

- Typical single-lepton $t\bar{t}$ selection (w/soft-muon b tag)
- Typical kinematic reconstruction and global event interpretation
- Λ_b reconstruction (using inclusive, semi-inclusive or exclusive approach) and polarization measurement

Measurement of b polarization in $t\bar{t}$



Statistical precision of about 10% possible at ATLAS/CMS in Run 2 (with 100/fb of data)

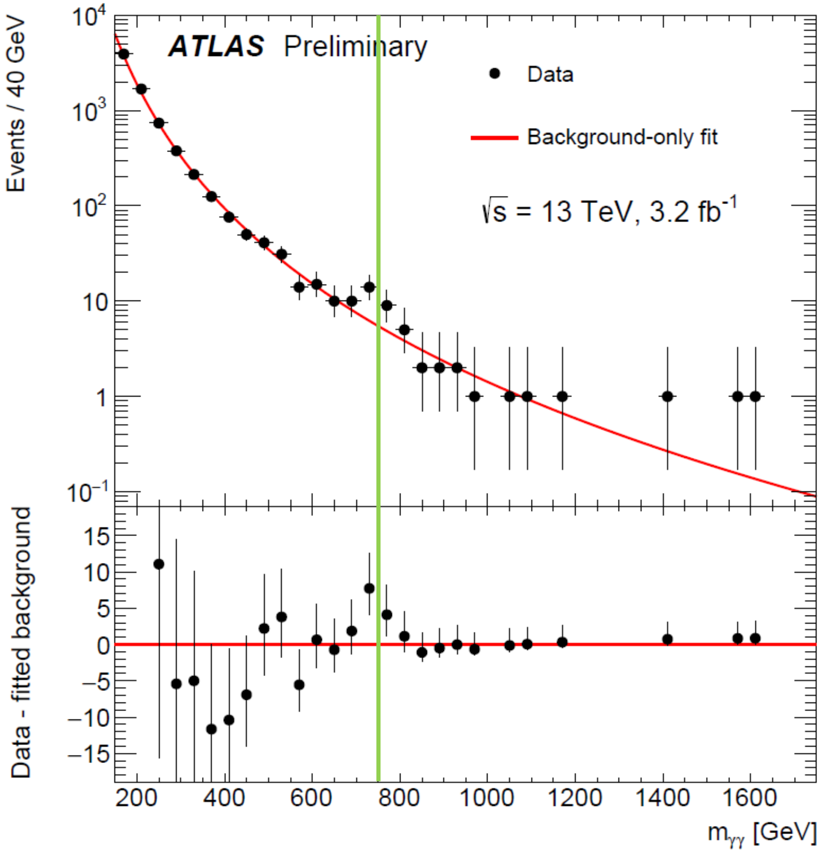
Selection	Expected events		
Baseline	$3\times10^6\ t\bar{t}+\mathcal{O}(10^6)$ bkg		
Soft-muon b tagging	$5\times10^5\ t\bar{t}+\mathcal{O}(10^4)$ bkg		$r_L = 0.6$
Signal events ($t \to b \to \Lambda_b \to \mu\nu X_c$)		Purity (example)	$\Delta\mathcal{A}_{FB}/\mathcal{A}_{FB}$
Inclusive	34 400	$\mathcal{O}(f_{\text{baryon}})$ (e.g., 7%)	±7%
Semi-inclusive	$2300 \times (\epsilon_\Lambda/30\%)$	70%	±8%
Exclusive	$1040 \times (\epsilon_{\Lambda_c}/25\%)$	30%	±19%
		100%	±10%

Part 2

Top-quark samples as a hiding place for new physics

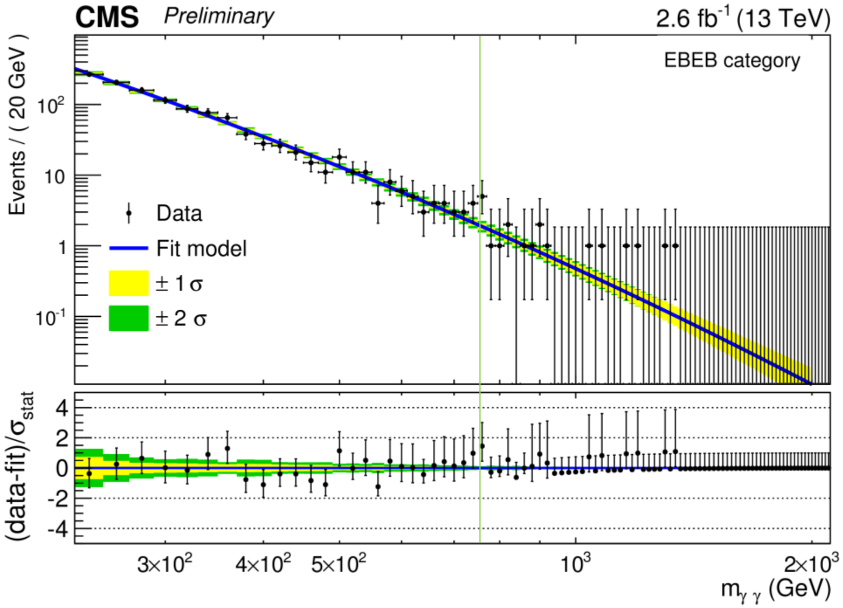
Original motivation

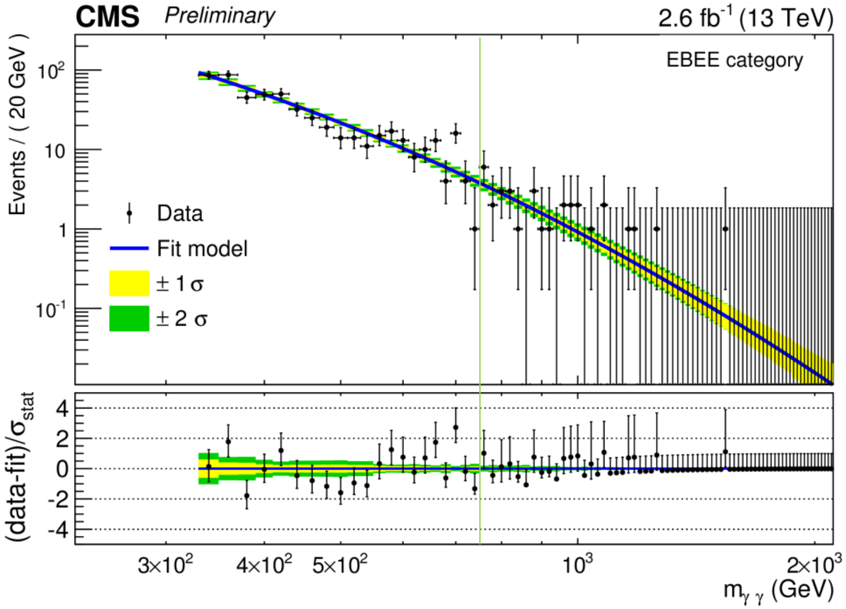
Resonant diphoton excesses
in ATLAS and CMS



$M \approx 750\,\mathrm{GeV}, \quad \Gamma \sim 0\text{-}100\,\mathrm{GeV}$

$\sigma \times \mathrm{BR}(\gamma\gamma) \sim 3\text{-}10\,\mathrm{fb}$





A simple explanation

Annihilation of a near-threshold bound state (X-onium) of a new colored and charged particle X with mass near 375 GeV.

arXiv:1512.06670	Luo, Wang, Xu, Zhang, Zhu
arXiv:1602.08100	Han, Ichikawa, Matsumoto, Nojiri, Takeuchi
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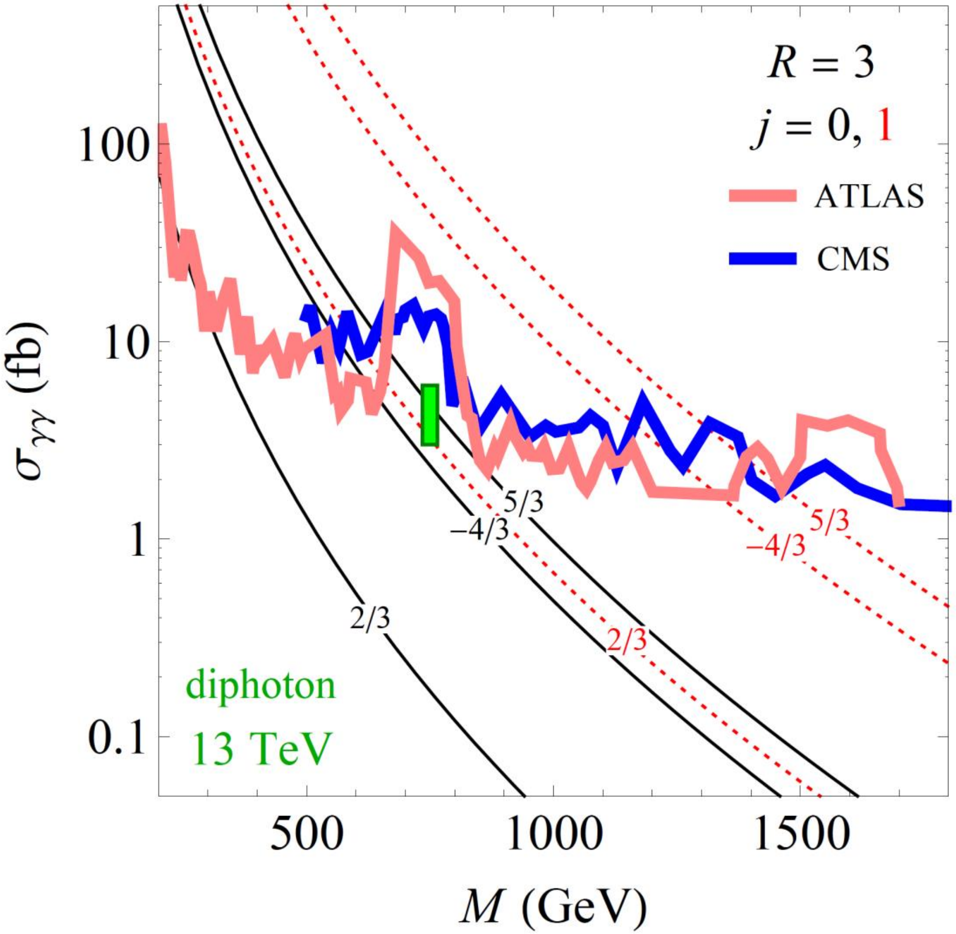
A long-anticipated colored and charged particle is the **stop**, but the stoponium signal would be too small.

Larger electric charge was needed to account for the excess.

Annihilation to photons



ATLAS (13 TeV, 3.2/fb)

ATLAS-CONF-2015-081

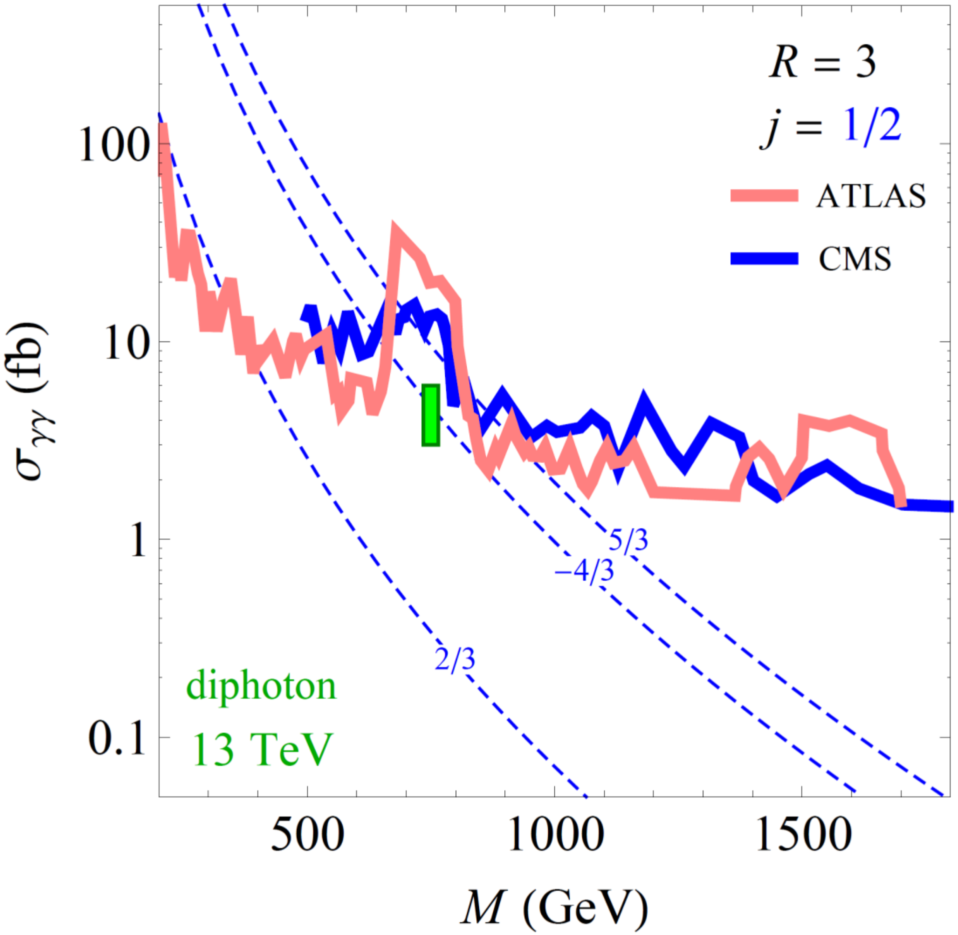
CMS (13 TeV, 2.6/fb)

CMS PAS EXO-15-004

Color-triplet scalars with $Q = -4/3$ or $5/3$ were candidates.

(In principle, also a vector with $Q = 2/3$.)

Annihilation to photons



ATLAS (13 TeV, 3.2/fb)

ATLAS-CONF-2015-081

CMS (13 TeV, 2.6/fb)

CMS PAS EXO-15-004

Color-triplet fermion with $Q = -4/3$ was a candidate.

A simple scenario

BSM particle content

scalar $X(3,1)_{-4/3}$ $\quad m_X \approx 375$ GeV

BSM interactions

$$\mathcal{L}_{\text{int}} = -\frac{c_{ij}}{2}\epsilon_{\alpha\beta\gamma}X^{*\alpha}\bar{u}_i^{\beta}\bar{u}_j^{\gamma} + \text{h.c.}$$

Main LHC phenomenology

$$gg,\, q\bar{q} \to XX^*, \qquad X \to \bar{u}\bar{c},\, \bar{t}\bar{u},\, \bar{t}\bar{c}$$

$$gg \to (XX^*) \to gg,\, ZZ,\, Z\gamma,\, \gamma\gamma$$

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Main LHC phenomenology

hiding in $t\bar{t}$+jets

$$gg,\ q\bar{q} \to XX^*, \quad X \to \bar{u}\bar{c}, \boxed{\bar{t}\bar{u},\ \bar{t}\bar{c}}$$

unconstrained

$$gg \to (XX^*) \to \underbrace{gg, ZZ, Z\gamma,}_{\text{unconstrained}}\ \underset{\text{excess}}{\gamma\gamma}$$

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unconstrained

$$gg \to (XX^*) \to \underbrace{gg, ZZ, Z\gamma,}_{\text{unconstrained}}\ \underset{\text{excess}}{\gamma\gamma}$$

But why would there be such a particle?

Doesn’t this scalar even introduce a new hierarchy problem?

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$$gg,\, q\bar{q} \to XX^*, \qquad X \to \bar{u}\bar{c}, \bar{t}\bar{u}, \bar{t}\bar{c}$$

unconstrained

$$gg \to (XX^*) \to \underbrace{gg, ZZ, Z\gamma,}_{\text{unconstrained}}\ \underset{\text{excess}}{\gamma\gamma}$$

But why would there be such a particle?

Maybe it is actually a top partner ;)

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hiding in $t\bar{t}$+jets

$$gg,\, q\bar{q} \to XX^*, \quad X \to \bar{u}\bar{c}, \boxed{\bar{t}\bar{u},\, \bar{t}\bar{c}}$$

unconstrained

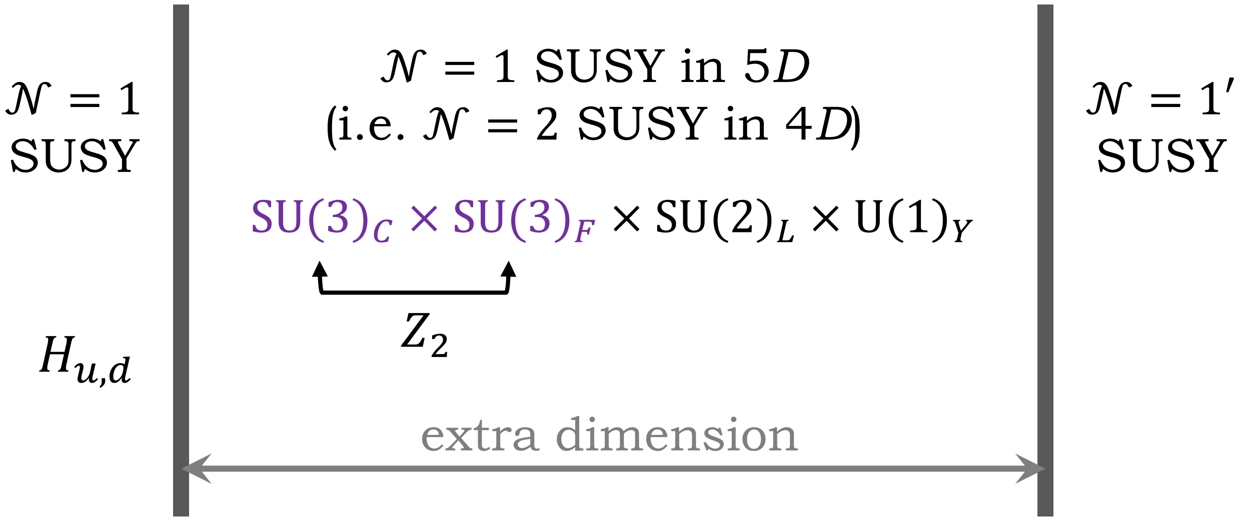
◆ For large c_{ij}, X-onium is unobservable (like the toponium), but the X may still be there!

But why would there be such a particle?

Maybe it is actually a top partner ;)

Reminder of “Folded SUSY”

Burdman, Chacko, Goh, Harnik, JHEP 02 (2007) 009 [hep-ph/0609152]



Members of $\mathcal{N} = 2$ supermultiplets and their boundary conditions

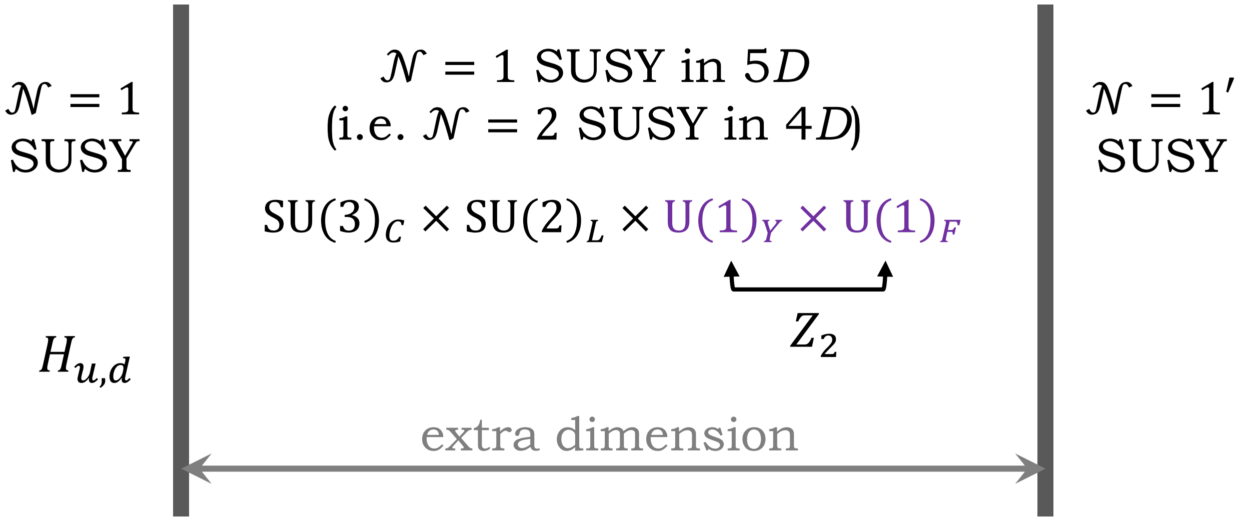
Z_2	**Quarks** $(\mathbf{3}, \mathbf{1}, \mathbf{SM}, \mathbf{SM})$	$\psi(++)$	$\psi^c(--)$	$\phi(+-)$	$\phi^c(-+)$
	Folded quarks $(\mathbf{1}, \mathbf{3}, \mathbf{SM}, \mathbf{SM})$	$\psi_F(+-)$	$\psi_F^c(-+)$	$\phi_F(++)$	$\phi_F^c(--)$

Importantly, the Higgs brane preserves the Z_2.

Divergences from top (ψ) are canceled by (colorless) “folded stops” (ϕ_F).

Our setup: "Hyperfolded SUSY"

preliminary



$\mathcal{N}=1$ SUSY

$\mathcal{N}=1$ SUSY in $5D$
(i.e. $\mathcal{N}=2$ SUSY in $4D$)

$\mathcal{N}=1'$ SUSY

$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \underbrace{\mathrm{U}(1)_Y \times \mathrm{U}(1)_F}_{Z_2}$

$H_{u,d}$

extra dimension

Members of $\mathcal{N}=2$ supermultiplets
and their boundary conditions

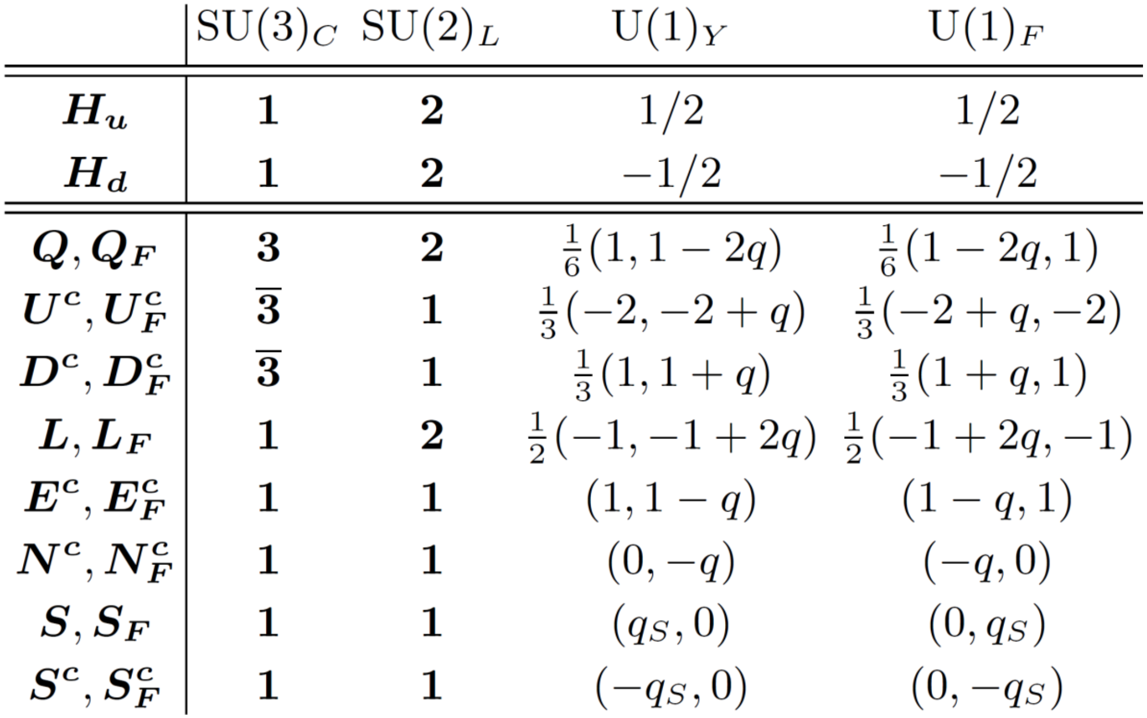
Z_2	**Quarks** $(\mathbf{SM},\mathbf{SM},\boldsymbol{Y}_{\mathbf{SM}},\boldsymbol{Y}_{\boldsymbol{F}})$	$\psi(++)$	$\psi^c(--)$	$\phi(+-)$	$\phi^c(-+)$
	Folded quarks $(\mathbf{SM},\mathbf{SM},\boldsymbol{Y}_{\boldsymbol{F}},\boldsymbol{Y}_{\mathbf{SM}})$	$\psi_F(+-)$	$\psi_F^c(-+)$	$\phi_F(++)$	$\phi_F^c(--)$

Importantly, the Higgs brane preserves the Z_2.

Divergences from top (ψ) are canceled by **colored** "folded stops" (ϕ_F) with **unconventional hypercharges**.

Our setup: “Hyperfolded SUSY”

preliminary



	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_F$
$\boldsymbol{H_u}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$1/2$
$\boldsymbol{H_d}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$-1/2$
$\boldsymbol{Q}, \boldsymbol{Q_F}$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}(1, 1-2q)$	$\frac{1}{6}(1-2q, 1)$
$\boldsymbol{U^c}, \boldsymbol{U^c_F}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}(-2, -2+q)$	$\frac{1}{3}(-2+q, -2)$
$\boldsymbol{D^c}, \boldsymbol{D^c_F}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}(1, 1+q)$	$\frac{1}{3}(1+q, 1)$
$\boldsymbol{L}, \boldsymbol{L_F}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}(-1, -1+2q)$	$\frac{1}{2}(-1+2q, -1)$
$\boldsymbol{E^c}, \boldsymbol{E^c_F}$	$\mathbf{1}$	$\mathbf{1}$	$(1, 1-q)$	$(1-q, 1)$
$\boldsymbol{N^c}, \boldsymbol{N^c_F}$	$\mathbf{1}$	$\mathbf{1}$	$(0, -q)$	$(-q, 0)$
$\boldsymbol{S}, \boldsymbol{S_F}$	$\mathbf{1}$	$\mathbf{1}$	$(q_S, 0)$	$(0, q_S)$
$\boldsymbol{S^c}, \boldsymbol{S^c_F}$	$\mathbf{1}$	$\mathbf{1}$	$(-q_S, 0)$	$(0, -q_S)$

$\Big\}$ for $\mathrm{U}(1)_F$ breaking

- Folded stops with **any charge** can be obtained by varying q. Charges of other fields are then constrained by $B - L$.
- The charge q_S (also a free parameter) determines the $\mathrm{U}(1)_F$-allowed operators for **decays**: $W \propto S_F \mathcal{O}_F$, where the operator $\mathcal{O}_F$ respects the SM gauge symmetries but not $\mathrm{U}(1)_F$.

Our setup: “Hyperfolded SUSY”

preliminary

Interesting decay examples

For a folded RH stop with $Q = -4/3$:

$$W \supset U_F^c U^c U^c$$

allows the decays

$$X \;\rightarrow\; \bar{u}\bar{c},\, \bar{t}\bar{u},\, \bar{t}\bar{c}$$

Our setup: “Hyperfolded SUSY”

preliminary

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Same decays are possible for a folded LH sbottom with $Q = -4/3$ (different scenario) via

$$W \supset D_F^c U^c U^c$$

in the presence of mixing.

Our setup: "Hyperfolded SUSY"

preliminary

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Same decays are possible for a folded LH sbottom with $Q = -4/3$ (different scenario) via

$$W \supset D_F^c U^c U^c$$

in the presence of mixing.

Alternatively, the sbottom may decay via

$$W \supset (H_u Q_F)(QQ)$$

as

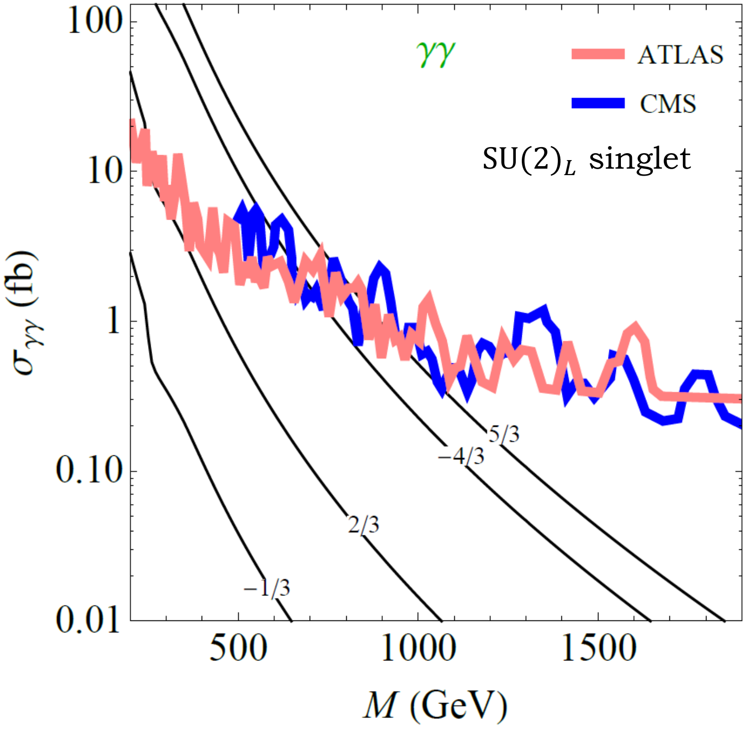
$$X \; \rightarrow W^- \bar{u}\bar{d}$$

Our setup: “Hyperfolded SUSY”

preliminary

Bound state signals

Higgs coupling induces sizable WW, ZZ, hh rates, leading to a reduction (e.g., factor of ~2) in the $\gamma\gamma$ rate.



Limits from:

ATLAS-CONF-2016-059 (15.4/fb)

CMS-PAS-EXO-16-027 (16.2/fb)

* Results shown are preliminary. Mixing with the Higgs not included.

Our setup: "Hyperfolded SUSY"

preliminary

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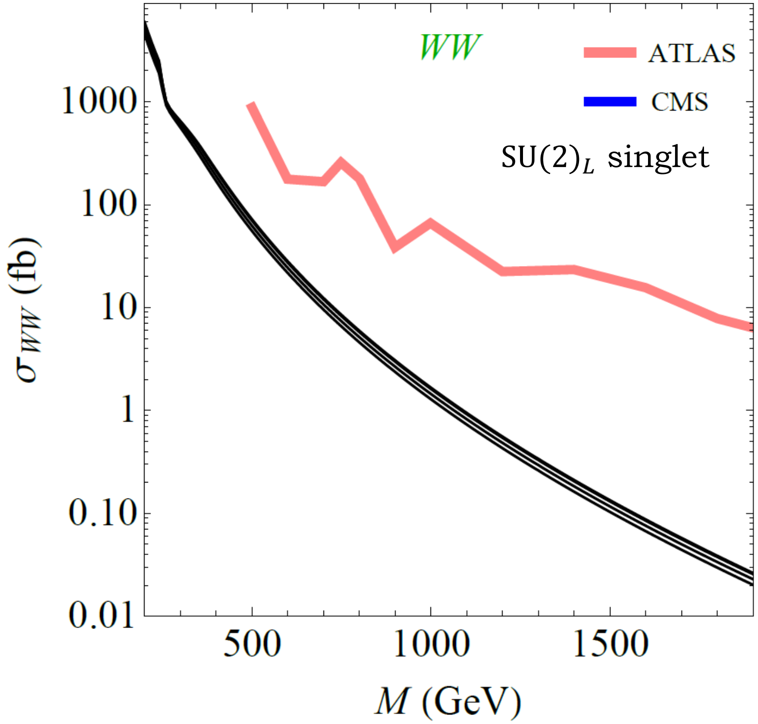

Limit from:

ATLAS-CONF-2016-062 ($\ell\nu qq$, 13.2/fb)

* Results shown are preliminary. Mixing with the Higgs not included.

Our setup: “Hyperfolded SUSY”

preliminary

Bound state signals

Higgs coupling induces sizable WW, ZZ, hh rates,

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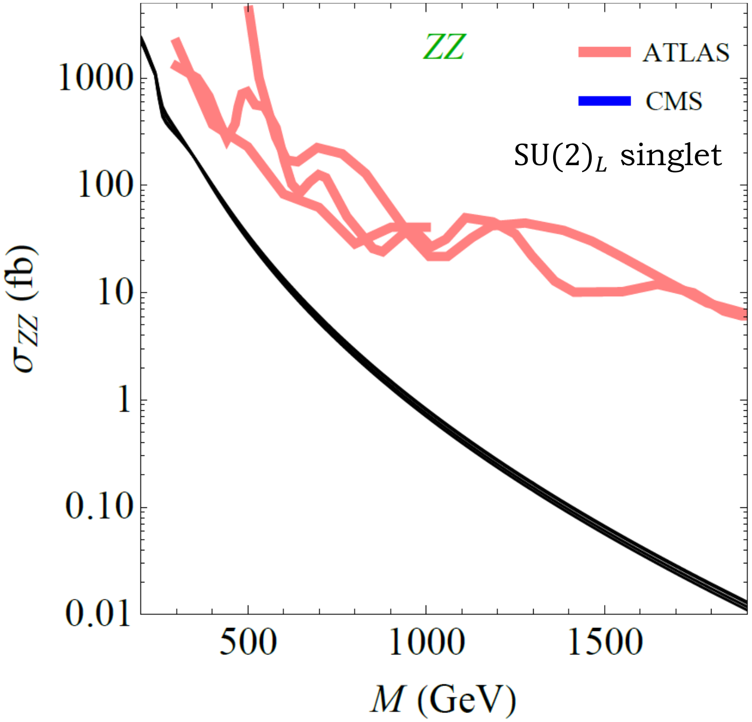

Limits from:

ATLAS-CONF-2016-056 ($\ell\ell\nu\nu$, 13.3/fb)

ATLAS-CONF-2016-082 ($\ell\ell qq$, 13.2/fb

$\nu\nu qq$, 13.2/fb)

* Results shown are preliminary. Mixing with the Higgs not included.

Our setup: “Hyperfolded SUSY”

preliminary

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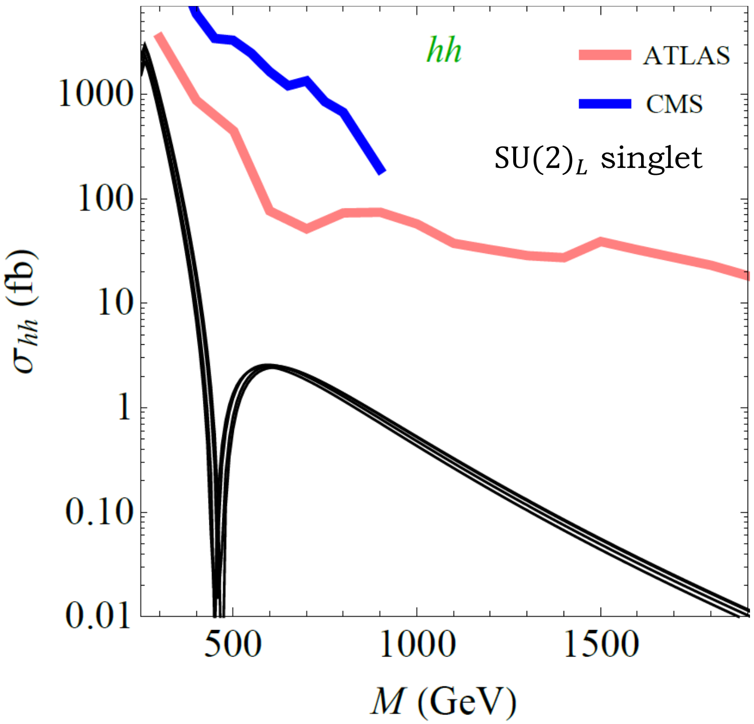

Limits from:
ATLAS-CONF-2016-049 ($bbbb$, 13.3/fb)
CMS-PAS-HIG-16-029 ($bb\tau\tau$, 12.9/fb)

* Results shown are preliminary. Mixing with the Higgs not included.

“Hyperfolded Composite Higgs”

or how to get spin-1/2 partners with unconventional charges

preliminary

Symmetry breaking pattern:

$$\mathrm{SU}(3)_G \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Z \to \mathrm{SU}(2)_L \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Y$$

$$\Phi \sim (\bar{3},1)_{\frac{1}{3}} = \exp\left(-i\frac{\pi^a T^a_G}{f}\right)\begin{pmatrix}0\\0\\f\end{pmatrix} \approx \begin{pmatrix}H\\ f-\frac{H^\dagger H}{2f}\end{pmatrix}$$

SM electroweak group generators:

$$T_L^{1,2,3} = T_G^{1,2,3} \qquad Y = Z - \frac{T_G^8}{\sqrt{3}} + \left(\frac{2}{3} - Y_T\right) T_X^3$$

free parameter, to become the top-partner hypercharge

“Hyperfolded Composite Higgs”

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free parameter, to become the top-partner hypercharge

The top sector:

$$Q \sim (3,2)_{\frac{Y_T}{2}} = \begin{pmatrix} b & q'_d \\ -t & -q'_u \\ t' & T \end{pmatrix} \qquad Q^c \sim (1,2)_{-\frac{Y_T}{2}-\frac{1}{3}} = \begin{pmatrix} T^c & t^c \end{pmatrix}$$

$\mathrm{SU}(2)_X$

“Hyperfolded Composite Higgs”

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preliminary

The Yukawa coupling $\mathcal{L}_Y = \lambda_t \epsilon_{\alpha\beta} Q^\alpha \Phi Q^{c\beta}$ translates to

$$\mathcal{L}_Y \supset \lambda_t q H t^c - \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) T T^c - \lambda_t q' H T^c + \lambda_t \left(f - \frac{H^\dagger H}{2f} \right) t' t^c + \mathcal{O}(1/f^2)$$

i.e., divergences due to top are canceled by the charge-Y_T partner.

	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Q_{EM}
H	1	2	$1/2$	
q	3	2	$1/6$	$2/3,\ -1/3$
t^c	$\bar{3}$	1	$-2/3$	$-2/3$
T	3	1	Y_T	Y_T
T^c	$\bar{3}$	1	$-Y_T$	$-Y_T$
q'	3	2	$Y_T - 1/2$	$Y_T,\ Y_T - 1$
q'^c	$\bar{3}$	2	$-(Y_T - 1/2)$	$-Y_T,\ -(Y_T - 1)$
t'	3	1	$2/3$	$2/3$
t'^c	$\bar{3}$	1	$-2/3$	$-2/3$

SM

Top partner X with arbitrary charge

Extra states + vectorlike partners (can be heavy)

“Hyperfolded Composite Higgs”

or how to get spin-1/2 partners with unconventional charges

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i.e., divergences due to top are canceled by the charge-Y_T partner.

This is just a toy model since it does not have custodial protection.
A similar but more complicated model (with additional light partners) seems possible using

$$\mathrm{SO}(5)_G \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Z \to \mathrm{SO}(4) \times \mathrm{SU}(2)_X \times \mathrm{U}(1)_Z$$

“Hyperfolded Composite Higgs”

or how to get spin-1/2 partners with unconventional charges

preliminary

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i.e., divergences due to top are canceled by the charge-Y_T partner.

Since the charge-Y_T partner does not mix with the SM quarks,
the usual decays to W/Z/h + quark are absent.

“Hyperfolded Composite Higgs”

or how to get spin-1/2 partners with unconventional charges

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Since the charge-Y_T partner does not mix with the SM quarks, the usual decays to W/Z/h + quark are absent.

Instead, the decay may proceed via a higher-dimensional operator. For example, the operator

$$\mathcal{L} \propto \bar{X}^\dagger_\alpha \bar{u}^\dagger_{i\beta} \bar{d}^\alpha_j \bar{d}^\beta_k + \text{h.c.}$$

may give the potentially elusive decays

$$X \rightarrow jjj,\ tjj$$

Conclusions

BSM faces LHC run-2 realities

12-16 September 2016 *DESY Hamburg*

Europe/Berlin timezone

A **run-2 reality** is that measurements of s, c, b polarizations can be calibrated with $\mathcal{O}(10\%)$ precisions.

If this is done, **BSM will have to face** this new tool of ours.

Conclusions

BSM faces LHC run-2 realities

12-16 September 2016 *DESY Hamburg*

Europe/Berlin timezone

The 750 is gone, but it has shown us
new ways of putting a checkmark
on the Higgs mass.

Thank You!

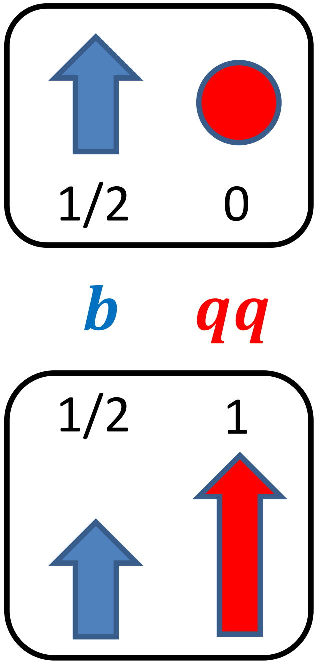
Supplementary Slides

b-quark polarization retention

chromomagnetic moment $\mu_b \propto \frac{1}{m_b}$

$m_b \gg \Lambda_{\mathrm{QCD}}$

b spin **preserved** during hadronization



Λ_b

b spin **preserved** during lifetime

Σ_b, Σ_b^*

b spin **oscillates** during lifetime

Λ_b sample contaminated by $\Sigma_b^{(*)} \rightarrow \Lambda_b \pi$

fragmentation fraction $f\,(b \rightarrow \text{baryons}) \approx 8\%$

b-quark polarization retention

Dominant polarization loss effect

$\Sigma_b^{(*)} \to \Lambda_b \pi$ decays

$$r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)} = ?$$

$$\left|\Lambda_{b,+1/2}\right\rangle = \left|b_{+1/2}\right\rangle \left|S_0\right\rangle$$

$$\left|\Sigma_{b,+1/2}\right\rangle = -\sqrt{\tfrac{1}{3}}\left|b_{+1/2}\right\rangle \left|T_0\right\rangle + \sqrt{\tfrac{2}{3}}\left|b_{-1/2}\right\rangle \left|T_{+1}\right\rangle$$

$$\left|\Sigma^*_{b,+1/2}\right\rangle = \sqrt{\tfrac{2}{3}}\left|b_{+1/2}\right\rangle \left|T_0\right\rangle + \sqrt{\tfrac{1}{3}}\left|b_{-1/2}\right\rangle \left|T_{+1}\right\rangle$$

$$\left|\Sigma^*_{b,+3/2}\right\rangle = \left|b_{+1/2}\right\rangle \left|T_{+1}\right\rangle$$

diquarks

S	T
spin-0 isosinglet	spin-1 isotriplet

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diquarks

S	T
spin-0 isosinglet	spin-1 isotriplet

$$A = \frac{\mathrm{prob}\left(\Sigma_b^{(*)}\right)}{\mathrm{prob}\ (\Lambda_b)} = 9\ \frac{\mathrm{prob}(T)}{\mathrm{prob}(S)}$$

$$w_1 = \frac{\mathrm{prob}(T_{\pm 1})}{\mathrm{prob}(T)}$$

Falk and Peskin
PRD 49, 3320 (1994)
[hep-ph/9308241]

b-quark polarization retention

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Production as a b spin eigenstate.

Decay as a Σ_b or Σ_b^* mass eigenstate.

e.g. $\left|b_{+1/2}\right\rangle \left|T_0\right\rangle = -\sqrt{\tfrac{1}{3}}\,\left|\Sigma_{b,+1/2}\right\rangle + \sqrt{\tfrac{2}{3}}\,\left|\Sigma^*_{b,+1/2}\right\rangle$

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$$\boxed{r \approx \frac{1 + (1 + 4w_1)A/9}{1 + A}}$$

b-quark polarization retention

More precisely, need to account for $\Sigma_b^{(*)}$ widths (interference).

Parameter	(MeV)
Γ_{Σ_b}	7 ± 3
$\Gamma_{\Sigma_b^*}$	9 ± 2
$m_{\Sigma_b^*} - m_{\Sigma_b}$	21 ± 2

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$$|E\rangle \propto \int d\cos\theta \, d\phi \sum_{J,M} \langle J, M \,|\, \tfrac{1}{2}, +\tfrac{1}{2};\, 1, m\rangle \, \frac{p_\pi(E)}{E - m_J + i\Gamma(E)/2} \times$$

$$\times \sum_{s} \langle \tfrac{1}{2}, s;\, 1, M-s \,|\, J, M\rangle \, Y_1^{M-s}(\theta, \phi) \, |\theta, \phi\rangle \, |s\rangle$$

pion momentum

Λ_b spin

$$\rho(E) \propto \mathrm{Tr}_{\theta,\phi} \, |E\rangle \, \langle E|$$

$$\rho \propto \int_{m_{\Lambda_b}+m_\pi}^{\infty} dE \, p_\pi(E) \exp\left(-E/T\right) \rho(E)$$

phase space

statistical hadronization model ($T \approx 165$ MeV)

review: PLB 678, 350 (2009) [arXiv:0904.1368]

b-quark polarization retention

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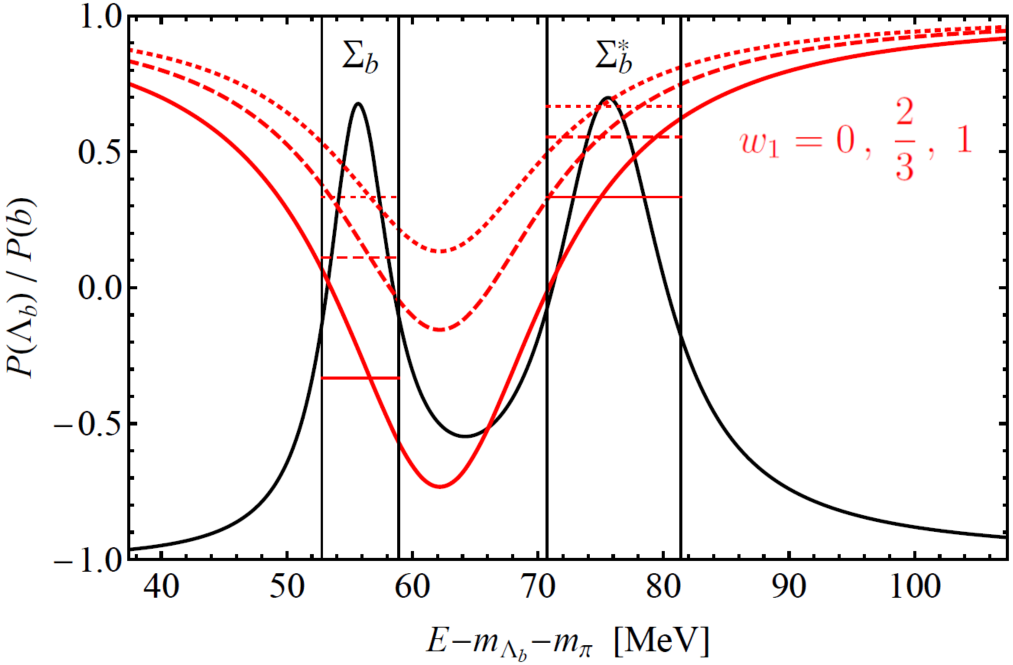
$m_{\Sigma_b^*} - m_{\Sigma_b}$	21 ± 2

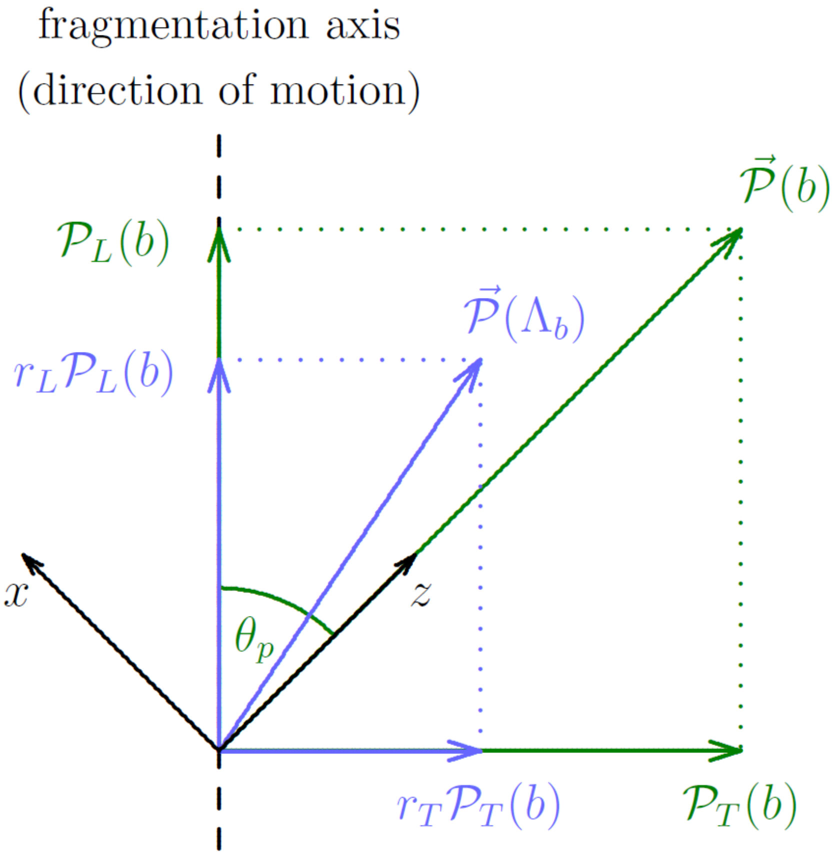


$$r \equiv \frac{\mathcal{P}(\Lambda_b)}{\mathcal{P}(b)} \approx \frac{1 + (0.23 + 0.38 w_1) A}{1 + A}$$

b-quark polarization retention

$w_1 = \dfrac{\mathrm{prob}(T_{\pm 1})}{\mathrm{prob}(T)}$ applies along the fragmentation axis.

If the b is polarized transversely, r is different.



$$r_L \approx \frac{1 + (0.23 + 0.38w_1)A}{1 + A}$$

$$r_T \approx \frac{1 + (0.62 - 0.19w_1)A}{1 + A}$$

b-quark polarization retention

Polarization retention factors:

$$r_L \approx \frac{1 + (0.23 + 0.38 w_1) A}{1 + A} \qquad r_T \approx \frac{1 + (0.62 - 0.19 w_1) A}{1 + A}$$

where

$$A = \frac{\text{prob}\left(\Sigma_b^{(*)}\right)}{\text{prob}\,(\Lambda_b)} = 9\,\frac{\text{prob}(T)}{\text{prob}(S)} \qquad w_1 = \frac{\text{prob}(T_{\pm 1})}{\text{prob}(T)}$$

What is known about A and w_1?

b-quark polarization retention

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Pythia tunes $0.24 \lesssim A \lesssim 0.45$ (based on light hadron data)

DELPHI (LEP) $1 \lesssim A \lesssim 10\ (b)$ $w_1 = -0.36 \pm 0.30 \pm 0.30\ (b)$

DELPHI-95-107

E791 $A \approx 1.1\ (c)$

PLB 379, 292 (1996) [hep-ex/9604007]

CLEO (CESR) $w_1 = 0.71 \pm 0.13\ (c)$

PRL 78, 2304 (1997)

Statistical hadronization model $A \approx 2.6$ (b and c)

review: PLB 678, 350 (2009) [arXiv:0904.1368]

Adamov-Goldstein model $A \approx 6$ (b and c) $w_1 \approx 0.41\ (b),\ 0.39\ (c)$

PRD 64, 014021 (2001) [hep-ph/0009300]

b-quark polarization retention

Polarization retention factors:

$$r_L \approx \frac{1 + (0.23 + 0.38w_1)A}{1 + A} \qquad r_T \approx \frac{1 + (0.62 - 0.19w_1)A}{1 + A}$$

where

$$A = \frac{\text{prob}\left(\Sigma_b^{(*)}\right)}{\text{prob}\ (\Lambda_b)} = 9\ \frac{\text{prob}(T)}{\text{prob}(S)} \qquad w_1 = \frac{\text{prob}(T_{\pm 1})}{\text{prob}(T)}$$

What is known about A and w_1?

Overall, $A \sim \mathcal{O}(1)$, $0 \leq w_1 \leq 1$ ⇨ $r_L, r_T \sim \mathcal{O}(1)$

consistent with Λ_b

measurements from LEP

Mass splittings and widths

bottom system

$$m_{\Lambda_b} = 5619.5 \pm 0.4 \text{ MeV}$$

Parameter	(MeV)
$m_{\Sigma_b} - m_{\Lambda_b}$	194 ± 2
$m_{\Sigma_b^*} - m_{\Lambda_b}$	214 ± 2
$\Delta \equiv m_{\Sigma_b^*} - m_{\Sigma_b}$	21 ± 2
Γ_{Σ_b}	7 ± 3
$\Gamma_{\Sigma_b^*}$	9 ± 2

charm system

$$m_{\Lambda_c} = 2286.5 \pm 0.2 \text{ MeV}$$

Parameter	(MeV)
$m_{\Sigma_c} - m_{\Lambda_c}$	167.4 ± 0.1
$m_{\Sigma_c^*} - m_{\Lambda_c}$	231.9 ± 0.4
$\Delta \equiv m_{\Sigma_c^*} - m_{\Sigma_c}$	64.5 ± 0.5
Γ_{Σ_c}	2.2 ± 0.2
$\Gamma_{\Sigma_c^*}$	15 ± 1

Measurement of b polarization in Z decays

***Z* production:** $pp \to Z \to b\bar{b}$

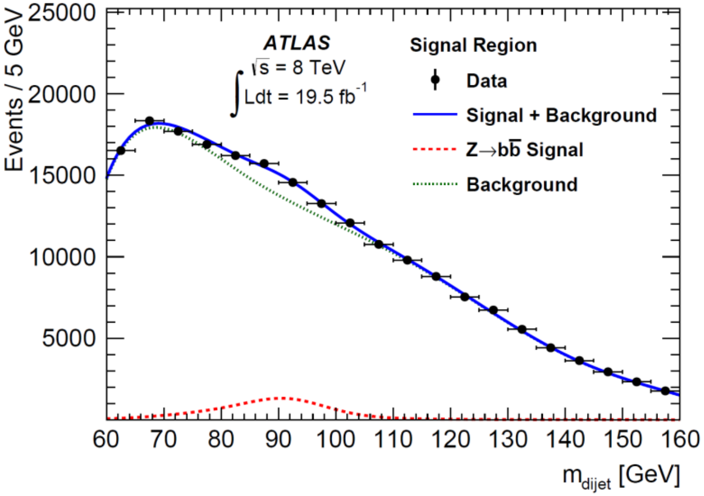
- Longitudinally polarized b quarks (similar to $t\bar{t}$)
- Large cross section

$$\frac{\sigma(pp \to Z \to b\bar{b})}{\sigma(pp \to t\bar{t} \to W^+W^-b\bar{b})} \sim 10$$

- Large QCD background (at 8 TeV, S/B ≈ 1/15 even for $p_T^Z > 200$ GeV) dilutes the asymmetry.

Probably less effective than $t\bar{t}$.

→



PLB 738, 25 (2014)
[arXiv:1404.7042]

Measurement of b polarization in QCD events

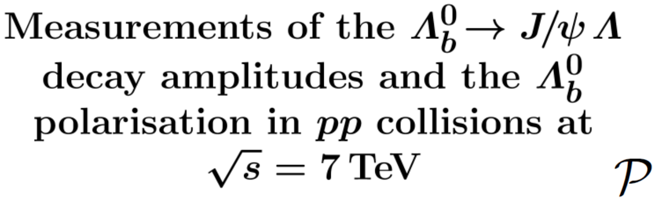
QCD production: $pp \to b\bar{b} + X$

- Large cross section
- Unpolarized at leading order
- *Transverse* polarization at NLO
- Strong dependence on kinematics
- Significant only at low momenta

$$\mathcal{P}(b) \sim \alpha_s m_b / p_b$$

Relevant (primarily) for LHCb

Existing LHCb analysis:



Measurements of the $\Lambda_b^0 \to J/\psi\,\Lambda$ decay amplitudes and the Λ_b^0 polarisation in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

PLB 724, 27 (2013)
[arXiv:1302.5578]

$$\mathcal{P}(\Lambda_b) = 0.06 \pm 0.07 \pm 0.02$$

Suboptimal because the dependence on kinematics is ignored.

Dharmaratna and Goldstein
PRD 53, 1073 (1996)

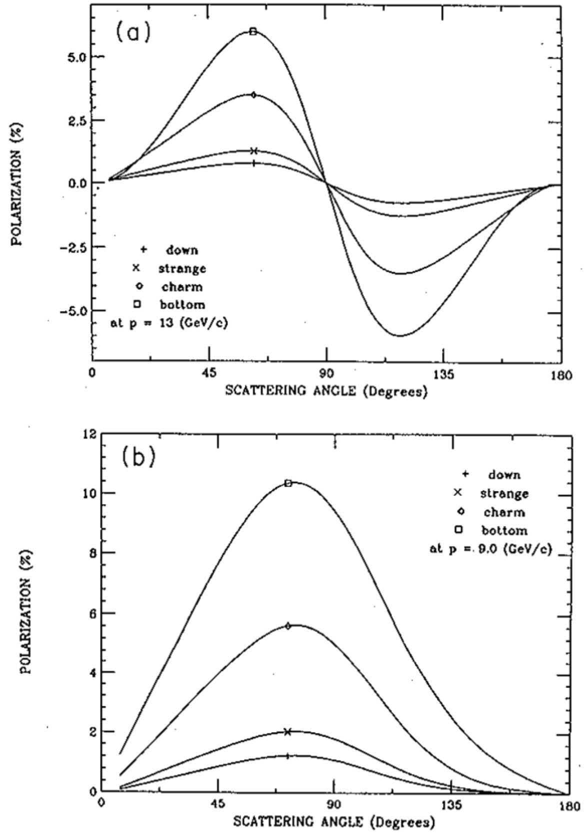
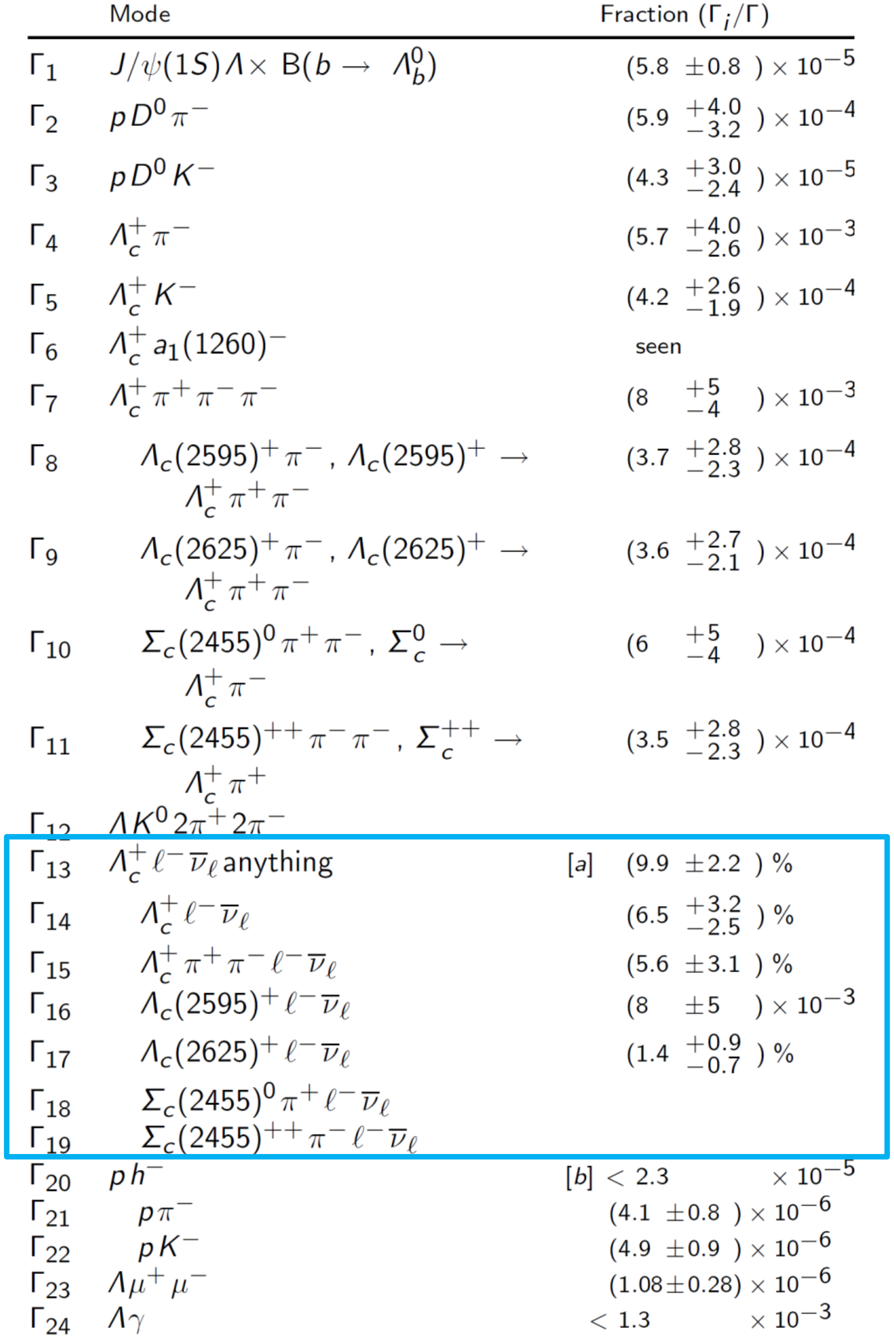


FIG. 7. Polarization of up, strange, charm, and bottom quarks at the subprocess CM momentum of (a) 13 GeV/c for gluon fusion and (b) 9 GeV/c for annihilation. Other parameters are identical to Fig. 5.

Λ_b polarization measurement

Which Λ_b decay to use?

Choose semileptonic mode, **inclusive** in charm hadrons (large BR, no hadronic uncertainties).



	Mode		Fraction (Γ_i/Γ)
Γ_1	$J/\psi(1S)\Lambda\times$ B$(b\to\Lambda_b^0)$		$(5.8\ \pm0.8\ )\times10^{-5}$
Γ_2	$pD^0\pi^-$		$(5.9\ ^{+4.0}_{-3.2}\ )\times10^{-4}$
Γ_3	pD^0K^-		$(4.3\ ^{+3.0}_{-2.4}\ )\times10^{-5}$
Γ_4	$\Lambda_c^+\pi^-$		$(5.7\ ^{+4.0}_{-2.6}\ )\times10^{-3}$
Γ_5	$\Lambda_c^+K^-$		$(4.2\ ^{+2.6}_{-1.9}\ )\times10^{-4}$
Γ_6	$\Lambda_c^+a_1(1260)^-$		seen
Γ_7	$\Lambda_c^+\pi^+\pi^-\pi^-$		$(8\ ^{+5}_{-4}\ )\times10^{-3}$
Γ_8	$\Lambda_c(2595)^+\pi^-$, $\Lambda_c(2595)^+\to\Lambda_c^+\pi^+\pi^-$		$(3.7\ ^{+2.8}_{-2.3}\ )\times10^{-4}$
Γ_9	$\Lambda_c(2625)^+\pi^-$, $\Lambda_c(2625)^+\to\Lambda_c^+\pi^+\pi^-$		$(3.6\ ^{+2.7}_{-2.1}\ )\times10^{-4}$
Γ_{10}	$\Sigma_c(2455)^0\pi^+\pi^-$, $\Sigma_c^0\to\Lambda_c^+\pi^-$		$(6\ ^{+5}_{-4}\ )\times10^{-4}$
Γ_{11}	$\Sigma_c(2455)^{++}\pi^-\pi^-$, $\Sigma_c^{++}\to\Lambda_c^+\pi^+$		$(3.5\ ^{+2.8}_{-2.3}\ )\times10^{-4}$
Γ_{12}	$\Lambda K^0 2\pi^+2\pi^-$		
Γ_{13}	$\Lambda_c^+\ell^-\overline{\nu}_\ell$ anything	[a]	$(9.9\ \pm2.2\ )\ \%$
Γ_{14}	$\Lambda_c^+\ell^-\overline{\nu}_\ell$		$(6.5\ ^{+3.2}_{-2.5}\ )\ \%$
Γ_{15}	$\Lambda_c^+\pi^+\pi^-\ell^-\overline{\nu}_\ell$		$(5.6\ \pm3.1\ )\ \%$
Γ_{16}	$\Lambda_c(2595)^+\ell^-\overline{\nu}_\ell$		$(8\ \pm5\ )\times10^{-3}$
Γ_{17}	$\Lambda_c(2625)^+\ell^-\overline{\nu}_\ell$		$(1.4\ ^{+0.9}_{-0.7}\ )\ \%$
Γ_{18}	$\Sigma_c(2455)^0\pi^+\ell^-\overline{\nu}_\ell$		
Γ_{19}	$\Sigma_c(2455)^{++}\pi^-\ell^-\overline{\nu}_\ell$		
Γ_{20}	ph^-	[b]	$< 2.3\ \times10^{-5}$
Γ_{21}	$p\pi^-$		$(4.1\ \pm0.8\ )\times10^{-6}$
Γ_{22}	pK^-		$(4.9\ \pm0.9\ )\times10^{-6}$
Γ_{23}	$\Lambda\mu^+\mu^-$		$(1.08\pm0.28)\times10^{-6}$
Γ_{24}	$\Lambda\gamma$		$< 1.3\ \times10^{-3}$

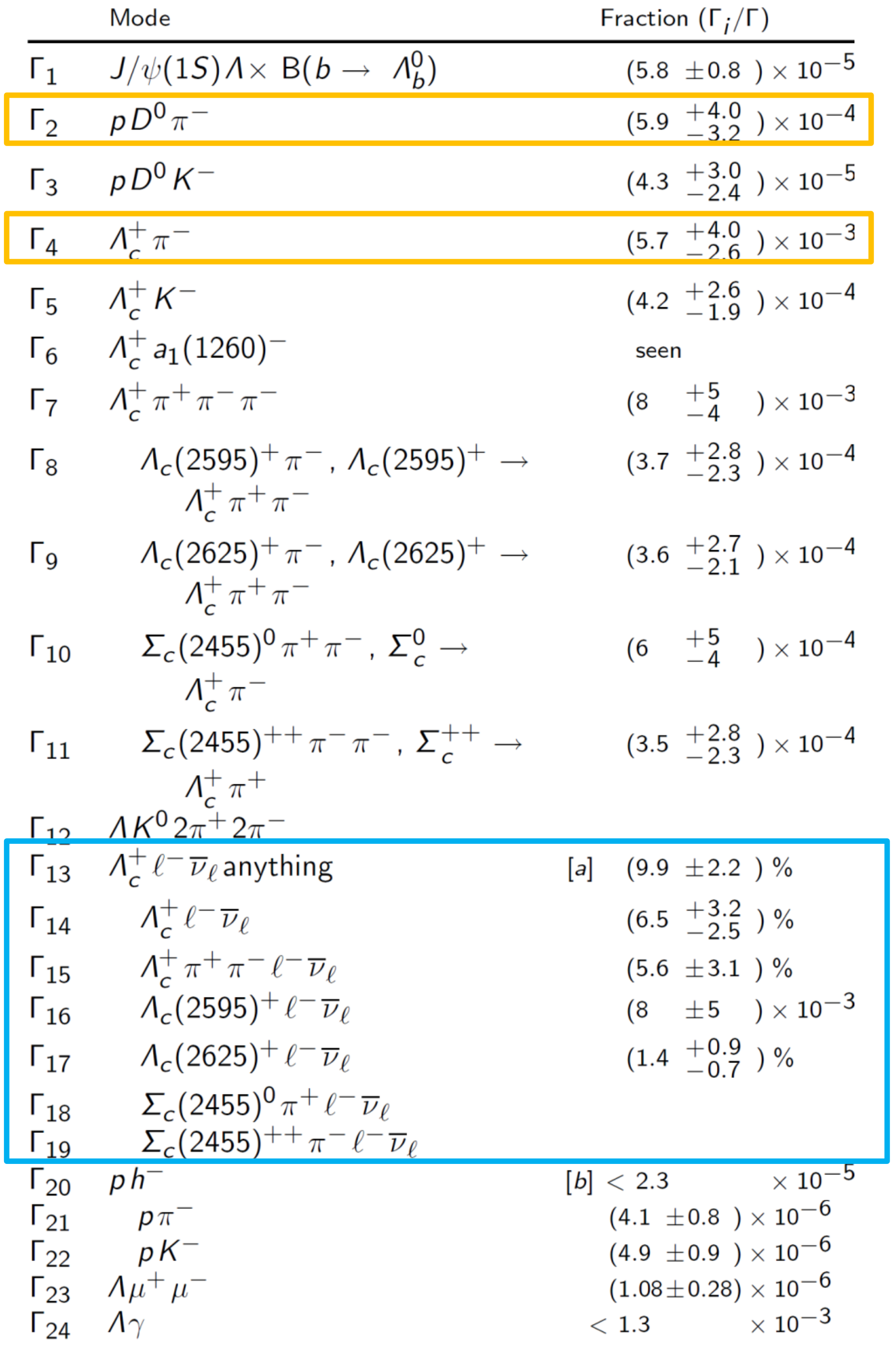
Λ_b polarization measurement

Which Λ_b decay to use?

Choose semileptonic mode, **inclusive** in charm hadrons (large BR, no hadronic uncertainties).

Includes also:

$\Lambda_b \rightarrow p\, D^0\, \ell^- \bar{\nu}_\ell$ small contribution



	Mode		Fraction (Γ_i/Γ)
Γ_1	$J/\psi(1S)\Lambda \times$ B$(b \to \Lambda_b^0)$		$(5.8\ \pm 0.8\ ) \times 10^{-5}$
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Γ_3	$p D^0 K^-$		$(4.3\ {}^{+3.0}_{-2.4}\ ) \times 10^{-5}$
Γ_4	$\Lambda_c^+ \pi^-$		$(5.7\ {}^{+4.0}_{-2.6}\ ) \times 10^{-3}$
Γ_5	$\Lambda_c^+ K^-$		$(4.2\ {}^{+2.6}_{-1.9}\ ) \times 10^{-4}$
Γ_6	$\Lambda_c^+ a_1(1260)^-$		seen
Γ_7	$\Lambda_c^+ \pi^+ \pi^- \pi^-$		$(8\ {}^{+5}_{-4}\ ) \times 10^{-3}$
Γ_8	$\Lambda_c(2595)^+ \pi^-$, $\Lambda_c(2595)^+ \to \Lambda_c^+ \pi^+ \pi^-$		$(3.7\ {}^{+2.8}_{-2.3}\ ) \times 10^{-4}$
Γ_9	$\Lambda_c(2625)^+ \pi^-$, $\Lambda_c(2625)^+ \to \Lambda_c^+ \pi^+ \pi^-$		$(3.6\ {}^{+2.7}_{-2.1}\ ) \times 10^{-4}$
Γ_{10}	$\Sigma_c(2455)^0 \pi^+ \pi^-$, $\Sigma_c^0 \to \Lambda_c^+ \pi^-$		$(6\ {}^{+5}_{-4}\ ) \times 10^{-4}$
Γ_{11}	$\Sigma_c(2455)^{++} \pi^- \pi^-$, $\Sigma_c^{++} \to \Lambda_c^+ \pi^+$		$(3.5\ {}^{+2.8}_{-2.3}\ ) \times 10^{-4}$
Γ_{12}	$\Lambda K^0 2\pi^+ 2\pi^-$		
Γ_{13}	$\Lambda_c^+ \ell^- \bar{\nu}_\ell$ anything	[a]	$(9.9\ \pm 2.2\ )$ %
Γ_{14}	$\Lambda_c^+ \ell^- \bar{\nu}_\ell$		$(6.5\ {}^{+3.2}_{-2.5}\ )$ %
Γ_{15}	$\Lambda_c^+ \pi^+ \pi^- \ell^- \bar{\nu}_\ell$		$(5.6\ \pm 3.1\ )$ %
Γ_{16}	$\Lambda_c(2595)^+ \ell^- \bar{\nu}_\ell$		$(8\ \pm 5\ ) \times 10^{-3}$
Γ_{17}	$\Lambda_c(2625)^+ \ell^- \bar{\nu}_\ell$		$(1.4\ {}^{+0.9}_{-0.7}\ )$ %
Γ_{18}	$\Sigma_c(2455)^0 \pi^+ \ell^- \bar{\nu}_\ell$		
Γ_{19}	$\Sigma_c(2455)^{++} \pi^- \ell^- \bar{\nu}_\ell$		
Γ_{20}	$p h^-$	[b]	$< 2.3 \times 10^{-5}$
Γ_{21}	$p \pi^-$		$(4.1\ \pm 0.8\ ) \times 10^{-6}$
Γ_{22}	$p K^-$		$(4.9\ \pm 0.9\ ) \times 10^{-6}$
Γ_{23}	$\Lambda \mu^+ \mu^-$		$(1.08 \pm 0.28) \times 10^{-6}$
Γ_{24}	$\Lambda \gamma$		$< 1.3 \times 10^{-3}$

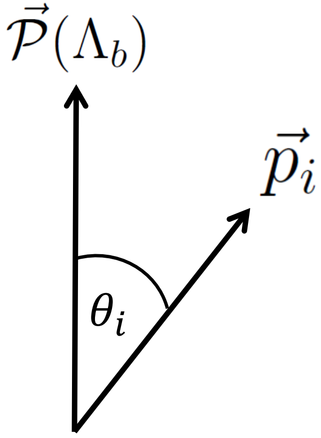
Λ_b polarization measurement

For the inclusive semileptonic decays

$$\Lambda_b \to X_c \ell^- \bar{\nu}$$

Λ_b polarization is encoded in the angular distributions

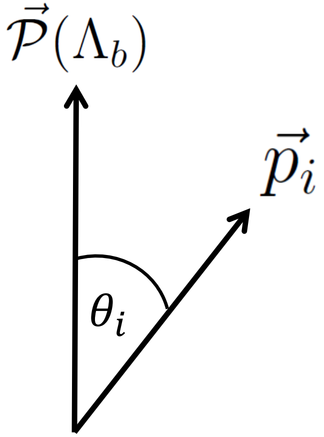
$$\frac{1}{\Gamma_{\Lambda_b}} \frac{d\Gamma_{\Lambda_b}}{d\cos\theta_i} = \frac{1}{2}\left(1 + \alpha_i \mathcal{P}\left(\Lambda_b\right)\cos\theta_i\right) \qquad i = \ell \text{ or } \nu$$



Λ_b polarization measurement

For the inclusive semileptonic decays

$$\Lambda_b \to X_c \ell^- \bar{\nu}$$



Λ_b polarization is encoded in the angular distributions

$$\frac{1}{\Gamma_{\Lambda_b}}\frac{d\Gamma_{\Lambda_b}}{d\cos\theta_i} = \frac{1}{2}\left(1 + \alpha_i\,\mathcal{P}\left(\Lambda_b\right)\cos\theta_i\right) \qquad i = \ell \text{ or } \nu$$

where

$$\alpha_\ell = \frac{-\frac{1}{3} + 4x_c + 12x_c^2 - \frac{44}{3}x_c^3 - x_c^4 + 12x_c^2\log x_c + 8x_c^3\log x_c}{1 - 8x_c + 8x_c^3 - x_c^4 - 12x_c^2\log x_c} \approx -0.26$$

$$\alpha_\nu = 1 \qquad\qquad x_c = \frac{m_c^2}{m_b^2}$$

$\mathcal{O}(\Lambda_{\rm QCD}/m_b)$ corrections are absent, and α_s corrections are few %.

Manohar, Wise
PRD 49, 1310 (1994)
[hep-ph/9308246]

Czarnecki, Jezabek, Korner, Kuhn, PRL 73, 384 (1994)
Czarnecki, Jezabek, NPB 427, 3 (1994)

Λ_b polarization measurement

$\Lambda_b \rightarrow X_c \ell^- \bar{\nu}$ (BR ≈ 10% per flavor)

- Soft-muon b tagging e.g. CMS-PAS-BTV-09-001
- Neutrino reconstruction using…
  - Λ_b mass constraint
  - Λ_b flight direction

Dambach, Langenegger, Starodumov
NIMA 569, 824 (2006) [hep-ph/0607294]

- Neutrino A_{FB} measurement (in the Λ_b rest frame)
- Approaches regarding semileptonic B-meson background:

Inclusive	keep it
Semi-inclusive	demand $\Lambda \rightarrow p\pi^-$ among decay products
Exclusive	demand a fully-reconstructible Λ_c decay

See paper for many additional details…

Λ_c polarization measurement

$\Lambda_c^+ \to pK^-\pi^+$ (BR ≈ 6.7%)

- Three tracks reconstructing the Λ_c mass.

- Backgrounds under the mass peak can be suppressed in various ways.

- Spin analyzing powers α_i seem to be large for K^-, small for p and π^+.

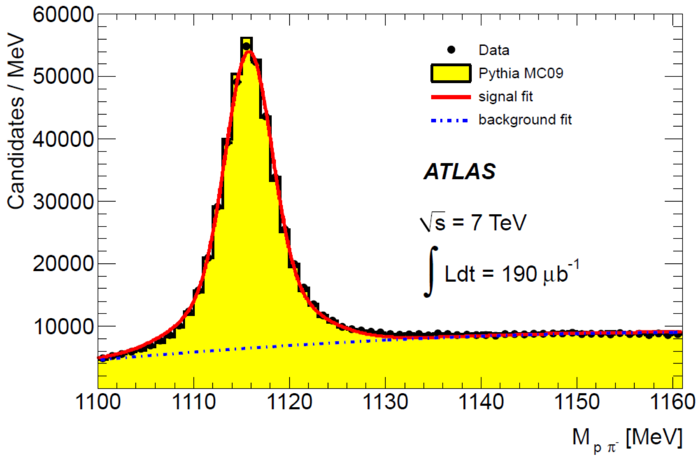
  NA32: Jeżabek, Rybicki, Ryłko, PLB 286, 175 (1992)

  Precise values not essential if SM calibration samples are available.

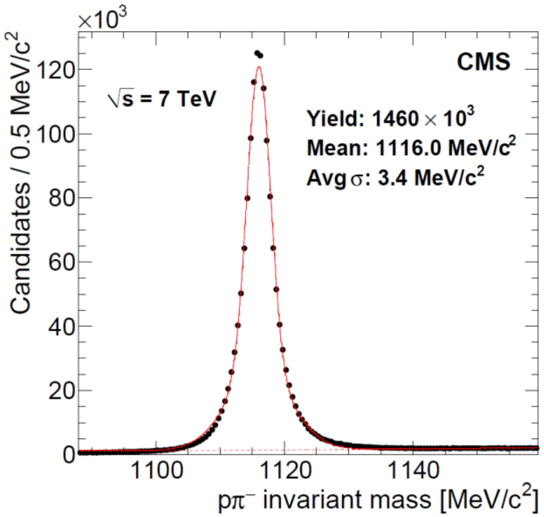
Λ polarization measurement

$$\Lambda \to p\,\pi^- \qquad \text{(BR} \approx 64\%\text{)}$$

- Pair of tracks from a highly displaced vertex reconstructing the Λ mass.
- Spin analyzing power $\alpha \approx 0.64$
- ATLAS and CMS already have experience with Λ's



PRD 85, 012001 (2012)
[arXiv:1111.1297]



JHEP 05, 064 (2011) [arXiv:1102.4282]

Measuring A directly

A is simply the ratio of the $\Sigma_b^{(*)}$ and Λ_b yields, independent of the b polarization:

$$A = \frac{\mathrm{prob}\left(\Sigma_b^{(*)}\right)}{\mathrm{prob}\left(\Lambda_b\right)} = 9\,\frac{\mathrm{prob}(T)}{\mathrm{prob}(S)}$$

Can be measured by any experiment that can see $\Sigma_b^{(*)} \to \Lambda_b \pi$: LHCb, ATLAS, CMS, maybe even re-analysis of Tevatron data.

CDF, PRL 99, 202001 (2007) [arXiv:0706.3868]

CDF, PRD 85, 092011 (2012) [arXiv:1112.2808]

Same for $\Sigma_c^{(*)}$ and Λ_c , where Belle and BaBar can also help.

Belle, PRD 89, 091102 (2014) [arXiv:1404.5389]

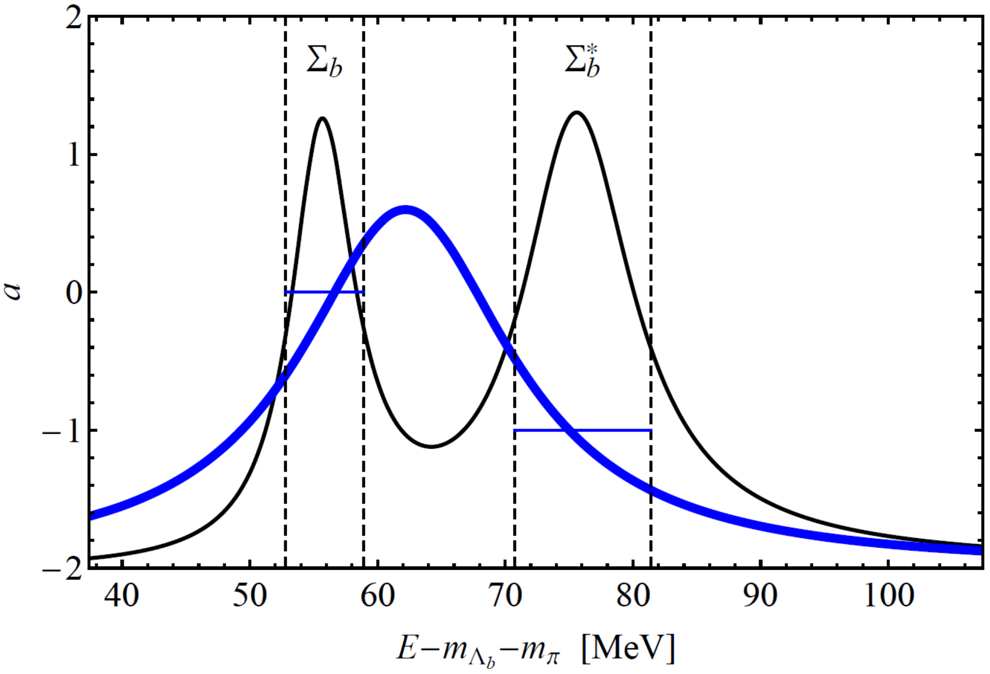
Measuring w_1 directly

The angular distribution of $\Sigma_b^{(*)} \to \Lambda_b \pi$ is sensitive to w_1, independent of the b polarization:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2} + \frac{9}{8}\,a\left(w_1 - \frac{2}{3}\right)\left(\cos^2\theta - \frac{1}{3}\right)$$

where a is given in the plot.

Can be measured by any experiment that can reconstruct these decays (see previous slide).



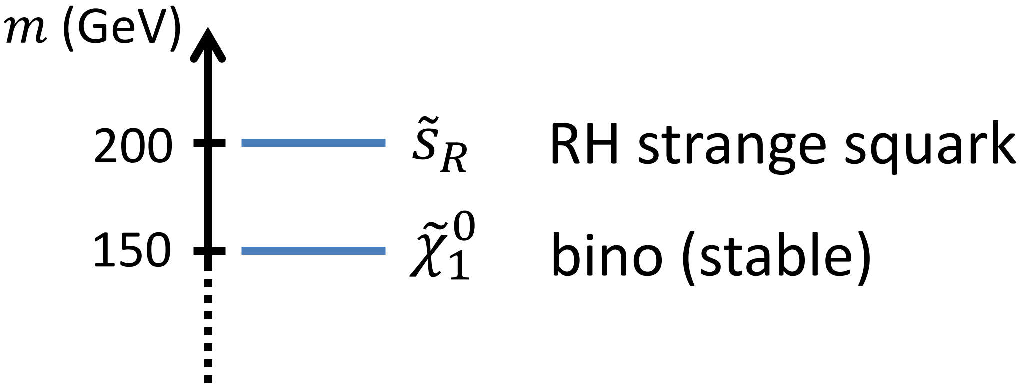
Same for $\Sigma_c^{(*)}$ and Λ_c.

New physics example

Suppose a jets + MET excess is being attributed to:

$pp \to \tilde{s}_R \tilde{s}_R^*$

$\tilde{s}_R \to s \tilde{\chi}_1^0$



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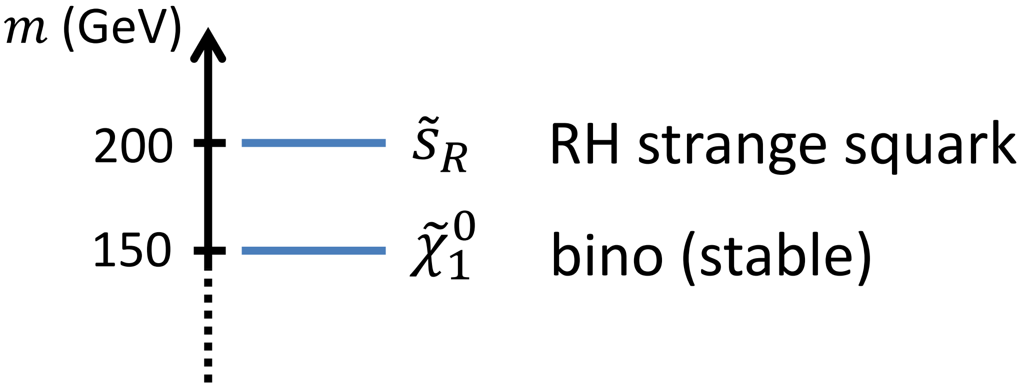
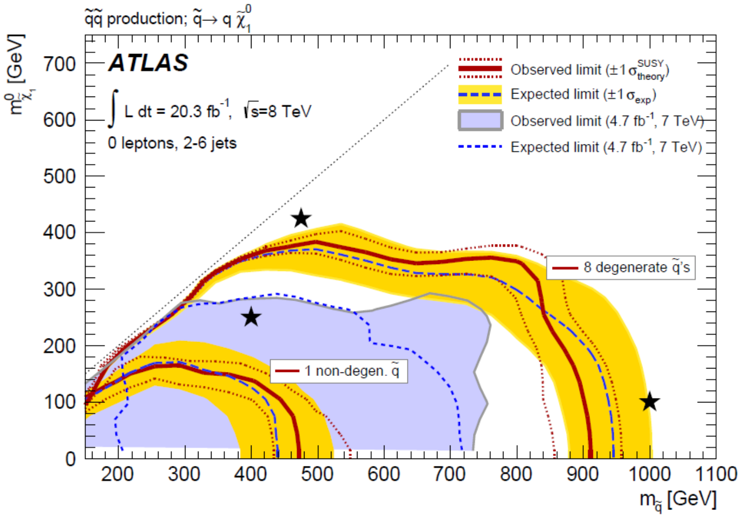
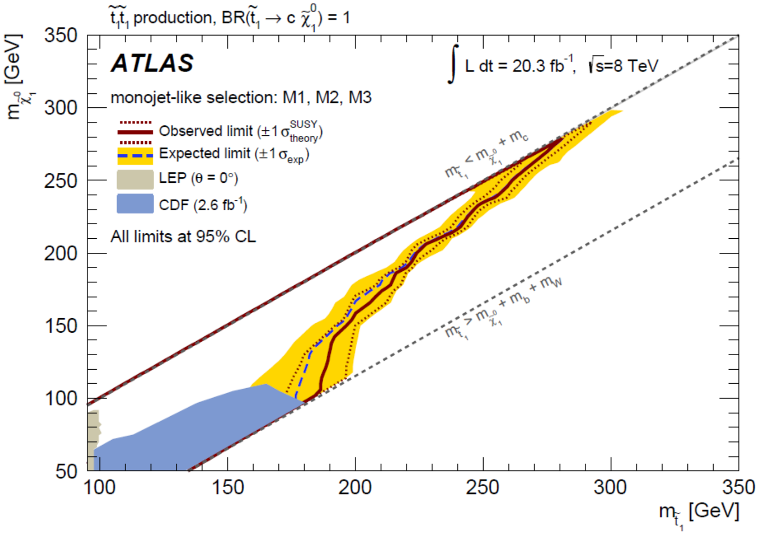


This scenario was barely beyond the reach of Run 1.



JHEP 09, 176 (2014) [arXiv:1405.7875]



PRD 90, 052008 (2014) [arXiv:1407.0608]

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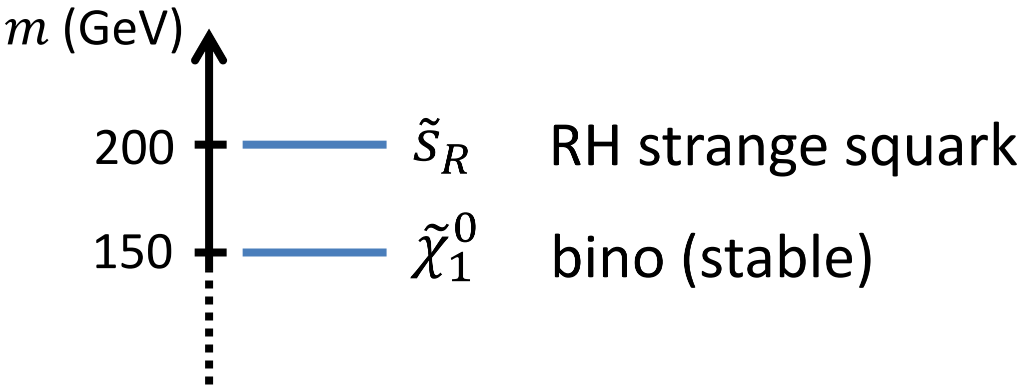
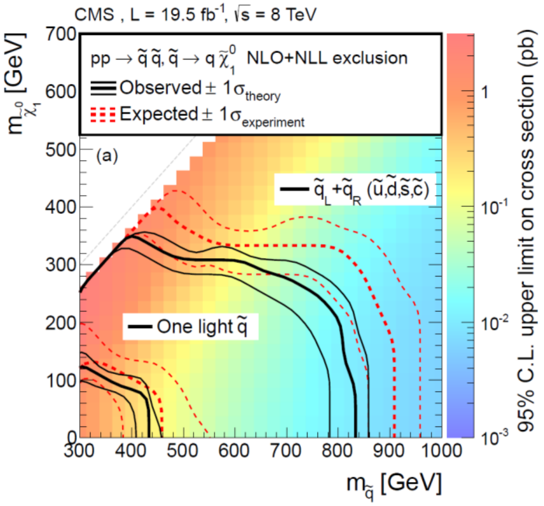
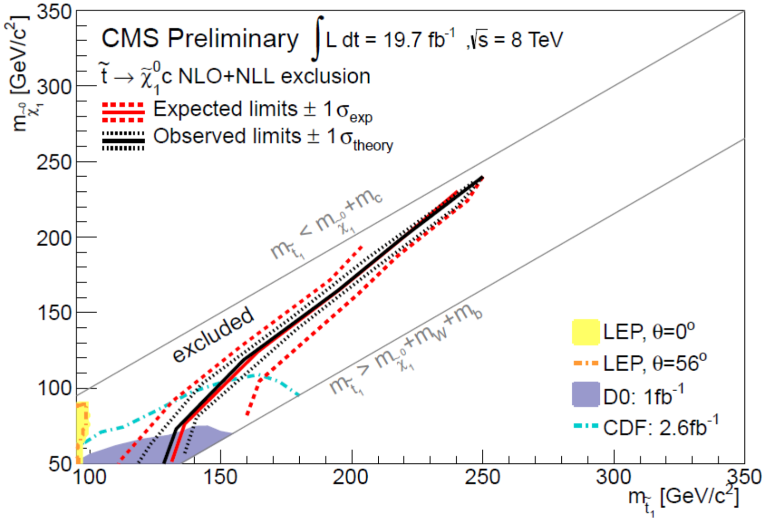


$\tilde{s}_R$ RH strange squark

$\tilde{\chi}_1^0$ bino (stable)

This scenario was barely beyond the reach of Run 1.





*The masses of interest are unfortunately not shown.

JHEP 06, 055 (2014) [arXiv:1402.4770]

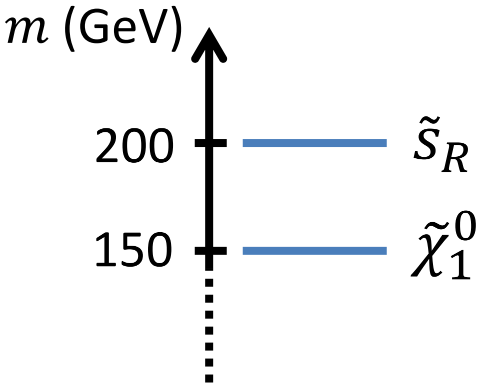
CMS-PAS-SUS-13-009

New physics example

Suppose a jets + MET excess is being attributed to:

$$pp \to \tilde{s}_R \tilde{s}_R^*$$

$$\tilde{s}_R \to s \tilde{\chi}_1^0$$



$\tilde{s}_R$ RH strange squark

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Test this interpretation by measuring the s-quark polarization.

New physics example

Suppose a jets + MET excess is being attributed to:

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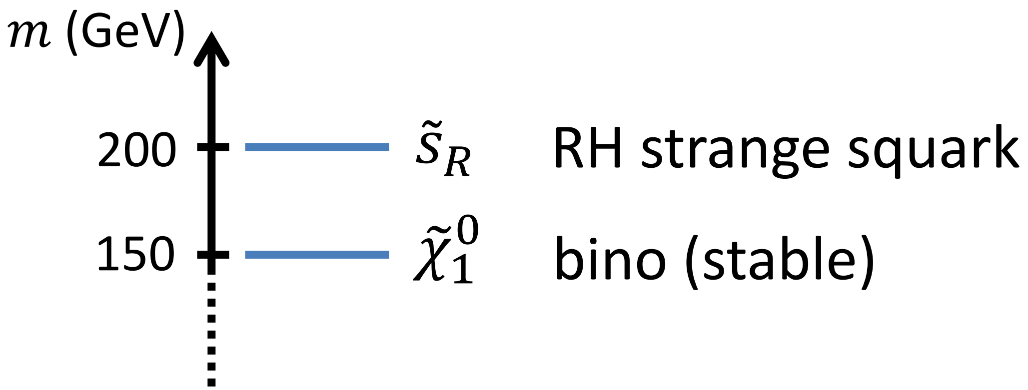

Test this interpretation by measuring the s-quark polarization.

Rough estimate (see paper for details):

for 3 ab^{-1} of 14 TeV data: statistical precision of better than **30%**

(even without optimization of selection cuts, without accounting for the expected detector upgrades, and without combining ATLAS and CMS)