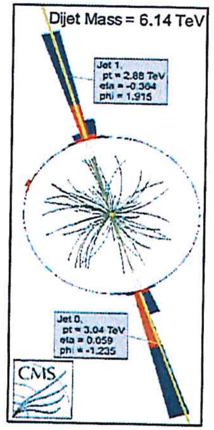
HELMHOLTZ ALLIANCE
TERASCALE PHYSICS SEMINAR
DESY 2/2/2017

F Hautmann

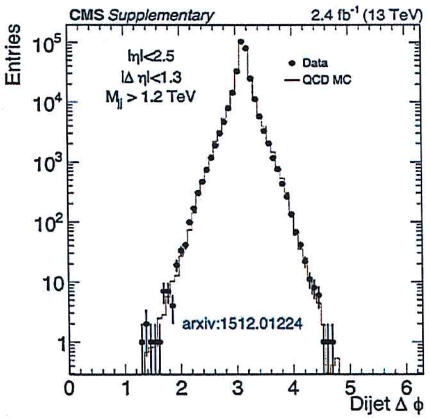
COLOR CORRELATIONS IN TOP QUARK AND JET PRODUCTION IN THE MULTI-TEV REGION

MULTI-TEV JETS

- MOTIVATED E.G. BY SEARCHES FOR BSM STATES DECAYING TO DI-JETS



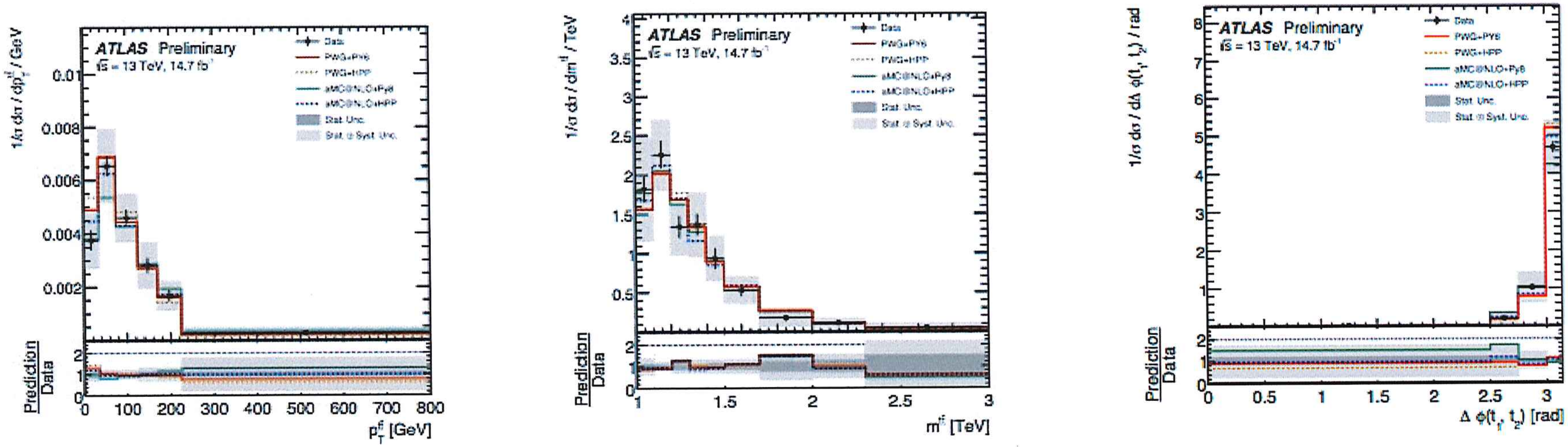
- MOST EVENTS ⇒ NEARLY BACK-TO-BACK JETS: $\Delta\phi \simeq \pi$



CMS Coll., PRL 116 (2016) 071801

IT IS KNOWN THAT IN THE BACK-TO-BACK REGION JETS ARE SENSITIVE TO QCD EFFECTS BEYOND FINITE PERTURBATIVE ORDER (LO, NLO, NNLO, ...)

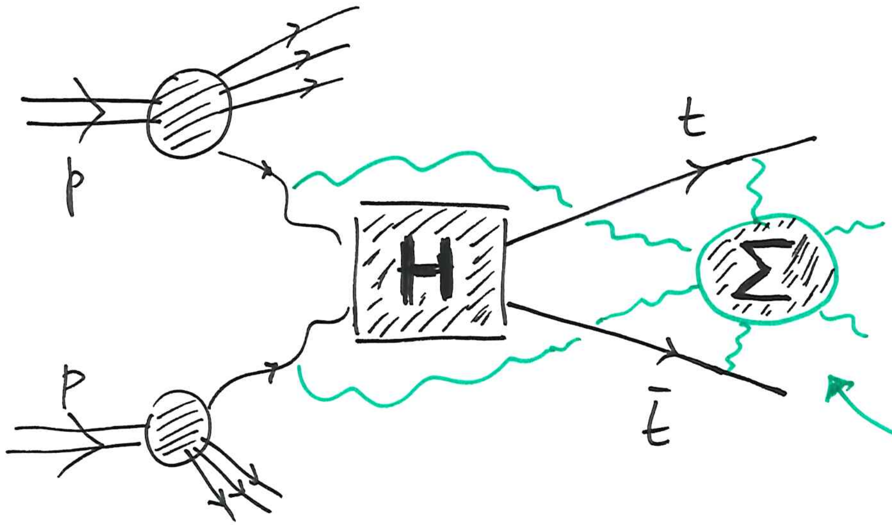
BOOSTED TOP QUARKS



ATLAS-2016-CONF-100

EFFECTS SIMILAR TO THE CASE OF MULTI-TEV JETS ARE EXPECTED IN BOOSTED TOP QUARK PRODUCTION.

COLOR CORRELATIONS



INITIAL-STATE / FINAL-STATE
COLOR CORRELATIONS

⇒ NEW "COLOR ENTANGLEMENT" EFFECTS?

- DO THESE CORRELATIONS CONTRIBUTE $\boxed{\text{BEYOND NLO \& LL}}$?
  (I.E., BEYOND THE LEVEL OF NLO-MATCHED PARTON SHOWER CALCULATIONS)
- TO WHAT EXTENT DO THEY AFFECT THE REGION $\boxed{M_{t\bar{t}} \gg \Delta p^{\perp}_{t\bar{t}}}$?
- SIGNIFICANT CORRECTIONS IN $\boxed{\alpha_s^m \ln^k (M/\Delta p^{\perp})}$, $k \leq 2m$, FOR ANY m
  TO TOP QUARK TRANSVERSE MOMENTUM SPECTRA AND ANGULAR CORRELATIONS ?

OUTLINE

- THEOR. : COLOR ENTANGLEMENT
- EXPT. : CURRENT STATUS OF NUMERICAL PREDICTIONS
- ONGOING WORK : ROLE OF INITIAL-STATE PARTON DISTRIBUTIONS?

  BEYOND THE CASE OF TOP QUARK?

TOP QUARK $p_\perp$ SPECTRA

SOFT GLUON RADIATION IN TOP QUARK $p_\perp$ SPECTRA STUDIED IN

- DIFFERENT LEVELS OF LOGARITHMIC ACCURACY →
- 1990's PAPERS DO NOT INCLUDE IS/FS CORRELATIONS

Berger & Meng (1994)
Mrenna & Yuan (1997)
Li, Li, Shao, Yang & Zhu (2013)
Catani, Grazzini & Torre (2014)

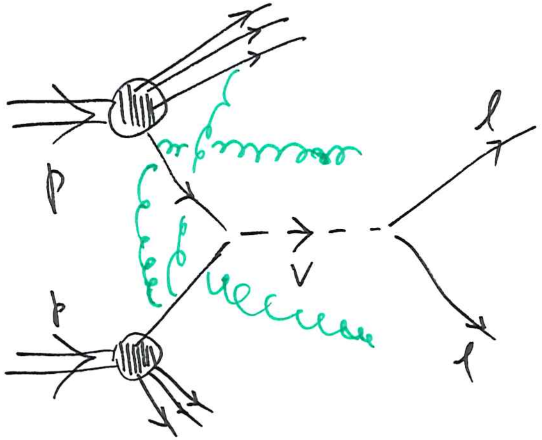
KEY IDEA: QCD FACTORIZATION AT FIXED TRANSVERSE COORDINATE

(*) TRADITIONALLY APPLIED TO COLOR SINGLET PRODUCTION (DY, ...)

(*) APPLICATION TO COLOR CHARGE PRODUCTION LEADS TO NOVEL "ENTANGLEMENT" EFFECTS

THE DRELL-YAN CASE

(NO COLOR CORRELATIONS)



- FACTOR MULTIPLE GLUON EMISSIONS IN TRANSVERSE b SPACE:

$$\delta\left(q_\perp - \sum_i p_{\perp i}\right) = e^{i\underline{b}\cdot\underline{q}_\perp} \prod_i e^{-i\underline{b}\cdot\underline{p}_{\perp i}}$$

- PREDICT CROSS SECTION AS

"hard"

$$\frac{d\sigma}{dq_\perp dQ^2} = \sum_{i,j} \int d^2b\, e^{i\underline{b}\cdot\underline{q}_\perp} H_{ij}\left(Q^2/\mu^2, \alpha_s(\mu)\right) \cdot f_i(x_1, b; \zeta_1, \mu) \cdot f_j(x_2, b; \zeta_2, \mu) \cdot$$

TMD pdf's

$$+ \left\{ q_\perp\text{-finite terms} \right\} + \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{Q^2}\right)$$

WHERE

$$\frac{\partial \ln f}{\partial \ln\sqrt{\zeta}} = K(\underline{b}, \mu)$$

COLLINS-SOPER-STERMAN EVOLUTION EQUATIONS

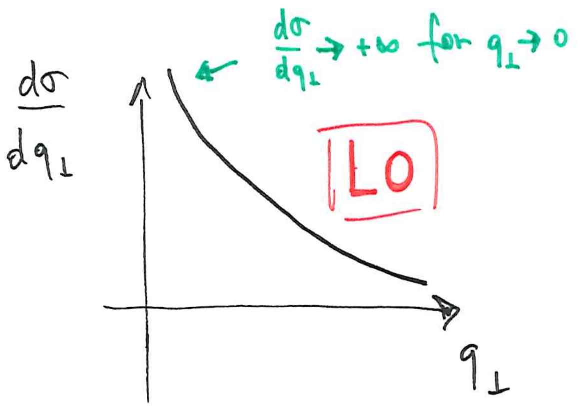
AND

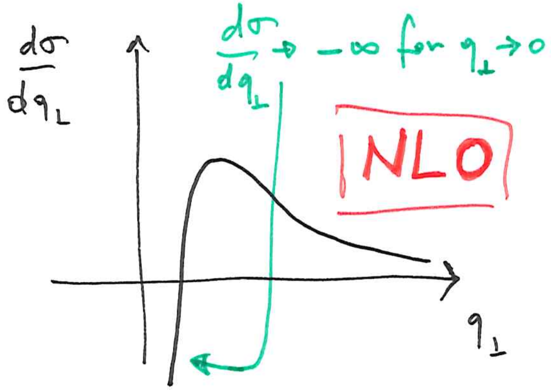
calculable as a perturbation series

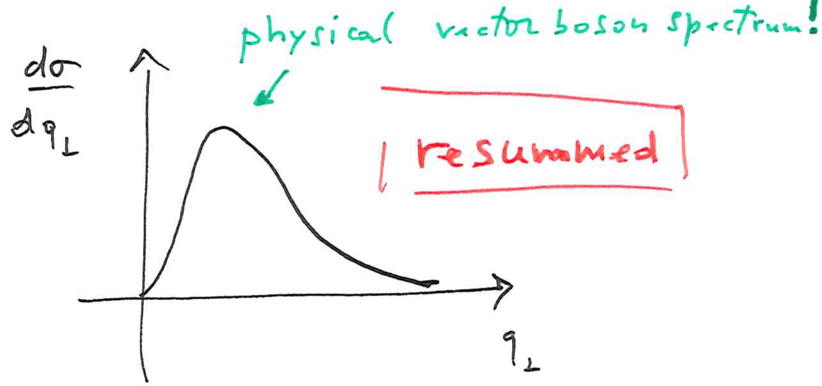
RG EVOLUTION $\rightarrow$ $$\frac{\partial \ln f}{\partial \ln \mu} = \gamma_f\left(\alpha_s(\mu), \zeta/\mu^2\right) \quad , \quad \frac{\partial K}{\partial \ln \mu} = -\gamma_K\left(\alpha_s(\mu)\right)$$ "CUSP ANOMALOUS DIMENSION"

$$\Rightarrow \; -\gamma_K = \frac{\partial}{\partial \ln\sqrt{\zeta}}\gamma_f \qquad \text{i.e.} \quad \gamma_f\left(\alpha_s(\mu), \zeta/\mu^2\right) = \gamma_f\left(\alpha_s(\mu), 1\right) - \frac{1}{2}\gamma_K \ln\zeta$$

- OUTCOME: SUM $\alpha_s^m \ln^k Q^2/q_\perp^2$ TO ALL ORDERS IN α_s







NOTE: SHOWER MONTE CARLO GENERATORS DO THIS "EFFECTIVELY"

• A MORE "PARTON-LIKE" FORMULATION IS ACHIEVED BY DECOMPOSING THE TMD PDF IN TERMS OF ORDINARY PDF's ("OPE")

$$\zeta = \mu \sim Q \sim b^{-1}$$

$$f_j(b,\mu) = S^{(j)}(Q,b)\; C_{ja}(b,\mu) \otimes f_a(\mu)$$

SUDAKOV FORM FACTOR (soft radiation)

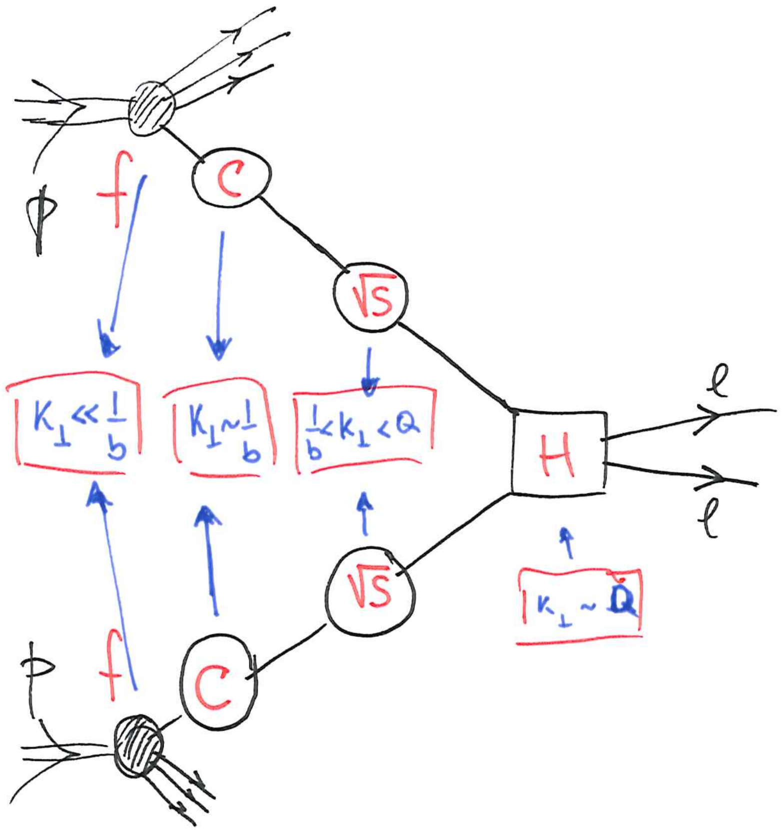
EVOLUTION KERNELS (collinear radiation)

INCLUSIVE PDF

$$\Downarrow$$

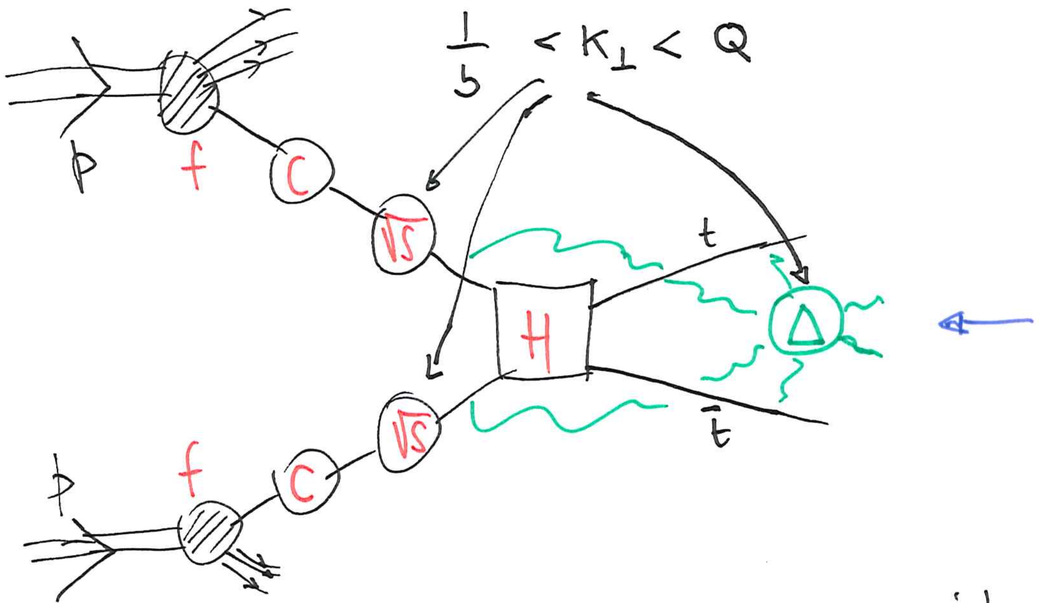
$$\left.\frac{d\sigma}{dq_\perp\, dQ^2}\right|_{res} = \sum_{\substack{i,j\\ a_1,a_2}} \int d^2b\; e^{i\underline{b}\cdot\underline{q}_\perp} \int_{x_1}^{1} dz_1 \int_{x_2}^{1} dz_2 \;\cdot$$

$$\cdot\, H_{ij}\, C_{ia_1}(z_1)\, C_{ja_2}(z_2)\, f_{a_1}\!\left(\frac{x_1}{z_1},\mu\right) f_{a_2}\!\left(\frac{x_2}{z_2},\mu\right)$$



THE $t\bar{t}$ CASE

WHAT CHANGES IN THE TOP QUARK PRODUCTION CASE?
THE MAIN DIFFERENCE IS DUE TO SOFT GLUONS, POSSIBLY AT LARGE ANGLES, COUPLING INITIAL STATE TO FINAL STATE.

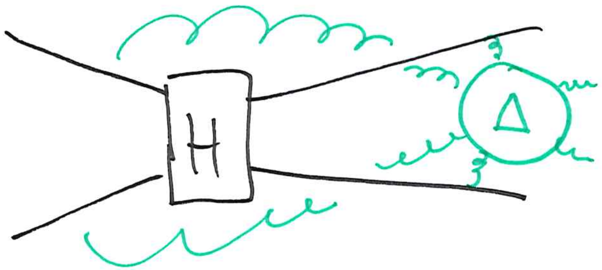


Δ = soft radiative factor
(REAL EMISSION + VIRTUAL CORRECTIONS)

$$\left.\frac{d\sigma}{dq_\perp dQ^2}\right)_{t\bar{t}} = \sum_{\substack{i,j\\a_1 a_2}} \int d^2b \, e^{i\underline{b}\cdot\underline{q}_\perp} \int_{x_1}^{1} dz_1 \int_{x_2}^{1} dz_2 \,\cdot$$

$$\cdot \left[\mathrm{Tr}(H\,\Delta)\; C_1\; C_2\right]_{ij a_1 a_2} f_{a_1}(x_1/z_1, \mu)\, f_{a_2}(x_2/z_2, \mu)$$

STRUCTURE OF SOFT RADIATIVE FACTOR



$\Longrightarrow$ color trace $\mathrm{Tr}[H\,\Delta]$

"COLOR ENTANGLEMENT"

$$\Delta(b,Q) = U^{\dagger}\, D\, U$$

COMPUTABLE AS POWER SERIES EXPANSIONS IN α_s

where $$U(b,Q) = \exp\left(-\int_{b^{-2}}^{Q^2} \frac{dq^2}{q^2}\,\Gamma(\alpha_s(q^2))\right)$$

Γ = soft anomalous dimension matrix

(*) Δ EMBODIES LONG-TIME COLOR CORRELATIONS BETWEEN INITIAL STATE AND FINAL STATE OF THE COLLISION

(*) D CONTAINS DEPENDENCE ON AZIMUTHAL ANGLE OF b $\Rightarrow$

$\Longrightarrow$ AZIMUTHAL CORRELATIONS

NOTE: TWO DISTINCT SOURCES OF AZIMUTHAL CORRELATIONS: $\underset{\text{soft}}{D}$ and $\underset{\text{collinear (gluon channel)}}{C}$

REMARKS

(*) THE CONTRIBUTIONS ENCODED IN THE $t\bar{t}$ FACTOR Δ FORM A SUBSET OF EFFECTS DUBBED "FACTORIZATION-BREAKING"

IN COLLINS & QIU (2007)
VOGELSANG & YUAN (2007)
ROGERS & MULDERS (2010)

- AT WHAT MOMENTUM SCALES DO THEY BECOME IMPORTANT?
- BOOSTED TOPS: DO EFFECTS MOVE TO HIGHER MOMENTUM SCALES?

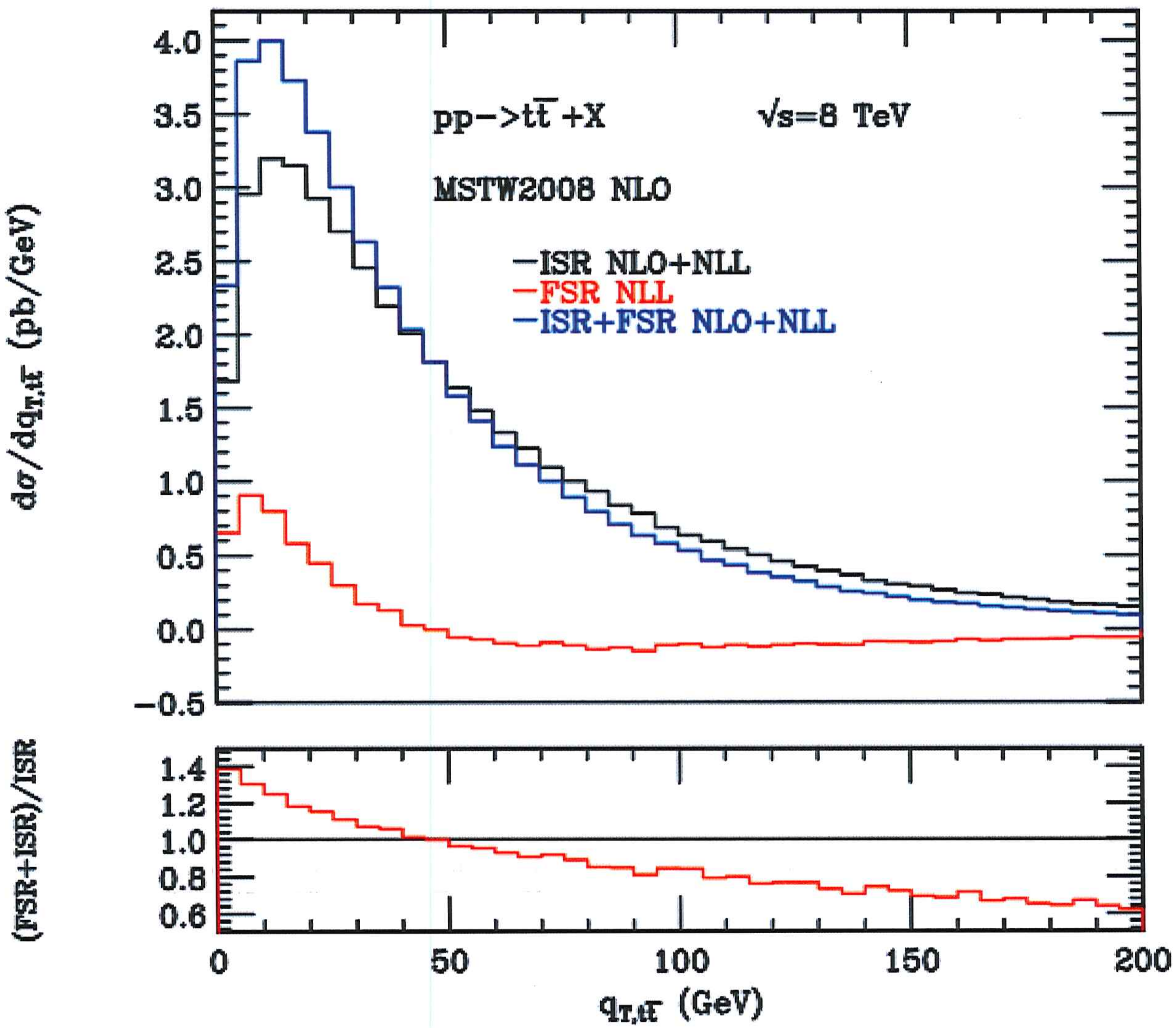
(*) UNTIL RECENTLY, NO NUMERICAL EVALUATION WAS AVAILABLE FOR THE SIZE OF SUCH EFFECTS.

THINGS ARE CHANGING $\longrightarrow$ H. SARGSYAN'S PRESENTATION AT CERN, JANUARY 2017

H. SARGSYAN, presentation at CERN, January 2017 (collaboration with R. Bonciani, S. Catani, M. Grazzini)

Preliminary results at NLO+NLL

- Large distortion of the spectrum due to soft radiation off the top quarks.



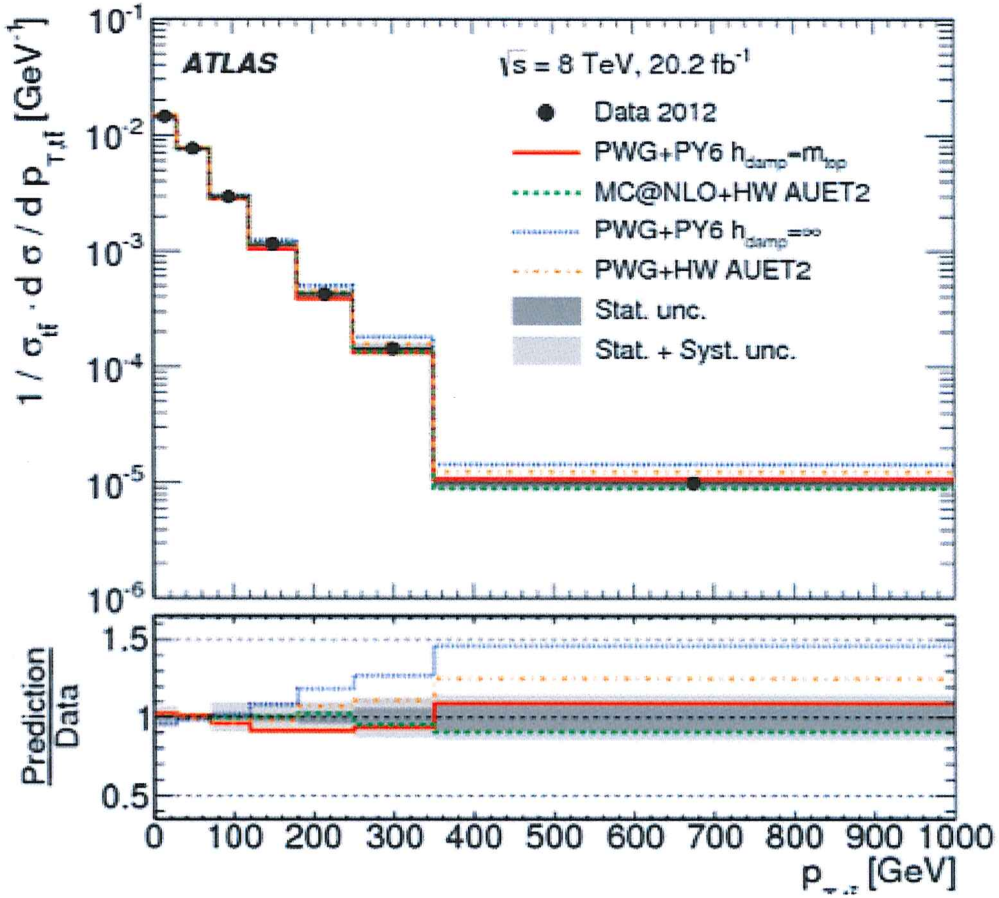
Resummation in MC event generators

q_T-resummation is effectively performed by Monte Carlo event generators.

- Based on the QCD factorization at the level of squared matrix elements.

In the case of strongly interacting final state particles the additional soft singularities are colour correlated.

- The large logs due to the soft radiation off the final state and due to the initial-final state interference are not under control through the shower.



H. SARGSYAN, presentation at CERN, January 2017 (collaboration with R. Bonciani, S. Catani, M. Grazzini)

THE CASE OF JETS

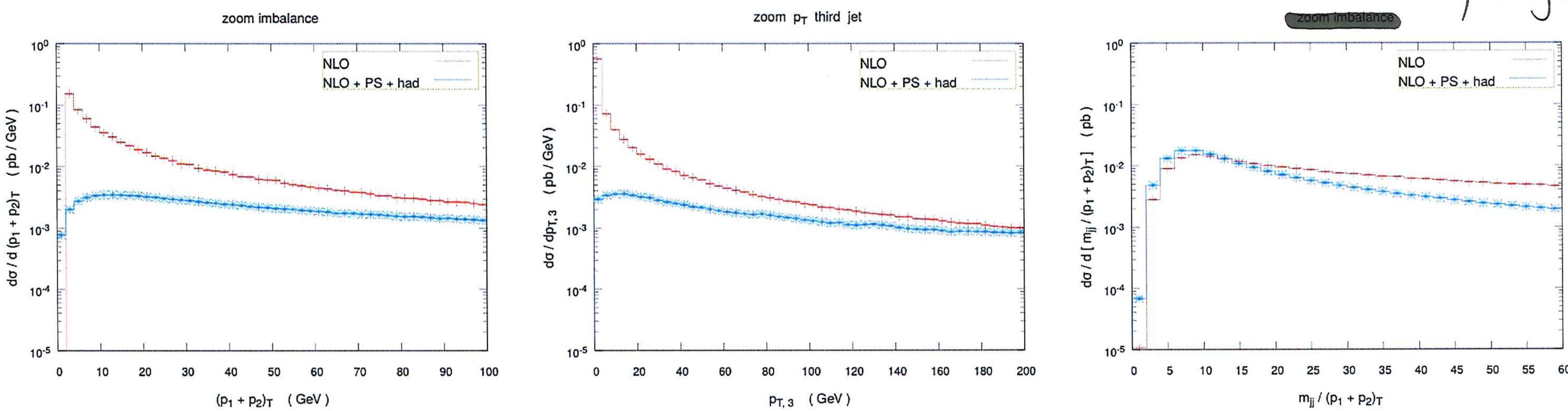
- COLLINEAR LIMIT IS SINGULAR FOR LIGHT QUARK JETS

  ⇒ NEW PATTERN OF COLOR CORRELATIONS?

  STRONGER ENTANGLEMENT EFFECTS?

NLO VS. PARTON SHOWER MONTECARLO SIMULATIONS (POWHEG):

M.V. Garzelli + FH, in progress



$p_{\perp_1} > 1.5$ TeV , $p_{\perp_2} > 1.2$ TeV

OUTLOOK

- HINTS OF $\mathcal{O}(30\%)$ EFFECTS FROM SOFT COLOR CORRELATIONS
- BUT "SOGGY" SCENARIO IN COMPARISONS WITH REALISTIC EVENT GENERATORS

HOW TO SHARPEN ANALYSIS OF CORRELATIONS?

(*) WHAT IS THE ROLE IN PARTON SHOWERS OF BOTH

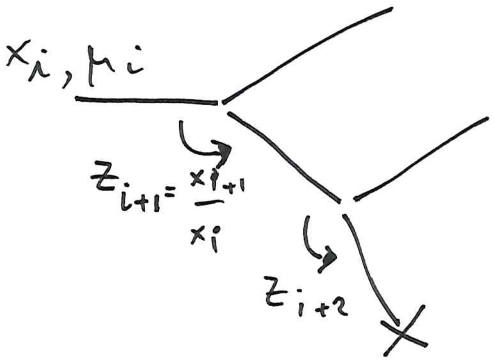
- "NON RESOLVABLE" GLUON EMISSIONS FOR $z \to 1$
- TRANSVERSE MOMENTA TRANSFERRED AT EACH BRANCHING

(*) CAN OTHER SCENARIOS BE HELPFUL BESIDES TOP QUARK PRODUCTION

A NEW APPROACH TO PARTON BRANCHING EVOLUTION

(with A. Lelek and H. Jung)

PARTON SHOWER VALID FOR VERY HIGH MASSES SHOULD INCORPORATE



- SOFT RADIATION $z \to 1$
- TRANSVERSE $q^\perp$ RECOILS AT EACH BRANCHING

(*) DECOMPOSE SPLITTING PROBABILITIES AS

$$P_{ab}(\alpha_s, z) = D_{ab}(\alpha_s)\,\delta(1-z) + K_{ab}(\alpha_s)\,\frac{1}{(1-z)_+} + R_{ab}(\alpha_s, z)$$

flavor diagonal

$$\int_0^1 \left(\frac{1}{1-z}\right)_+ \varphi(z)\,dz = \int_0^1 \frac{1}{1-z}\left[\varphi(z) - \varphi(1)\right] dz$$

log terms in $\ln(1-z)$ & analytic terms for $z \to 1$

VALID AT ANY LOOP ORDER

(∗) INTRODUCE RESOLUTION SCALE PARAMETER z_M

$$1 - z_M \sim \mathcal{O}\left(Q_0^2/Q^2\right) \quad ; \quad z > z_M : \text{ "non-resolvable" branchings}$$

$\Rightarrow$ 

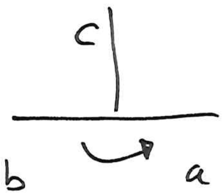
Sudakov form factor

$$\tilde{f}_a(x,\mu^2) = \tilde{f}_a(x,\mu_0^2)\, S_a(\mu^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{S_a(\mu^2)}{S_a(\mu'^2)} \int_x^{z_M} dz \,\cdot$$

$$\cdot \left[K_{ab}(\alpha_s(\mu'^2)) \frac{1}{1-z} + R_{ab}(\alpha_s(\mu'^2), z) \right] \tilde{f}_b(x/z, \mu'^2)$$

real-emission evolution kernel

(∗) USE BRANCHING KINEMATICS TO ASSOCIATE TRANSVERSE $q^\perp$ RECOILS WITH EVOLUTION VARIABLE:



$z = x_a / x_b$

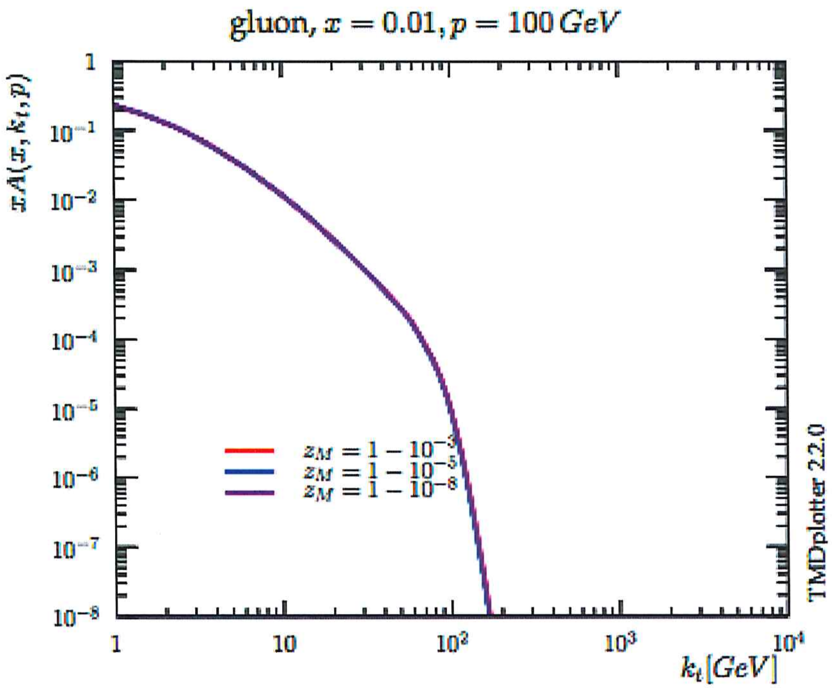
$$q_c^\perp = (1-z)\, E_b \sin\theta$$

$$\Rightarrow \quad q_c^{\perp\,2} = (1-z)\,\mu^2$$

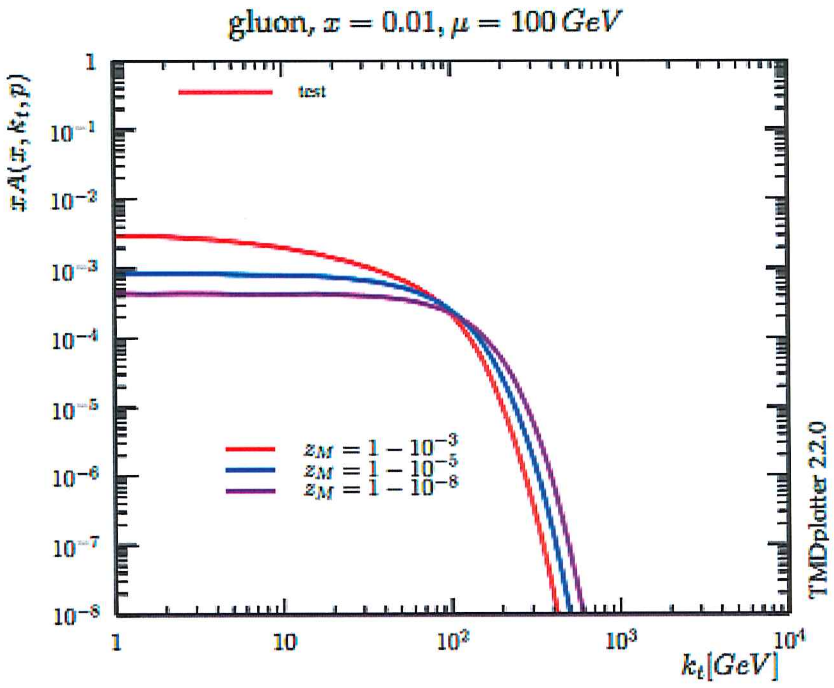
"angular ordering"

TRANSVERSE MOMENTUM DISTRIBUTION

angular ordering

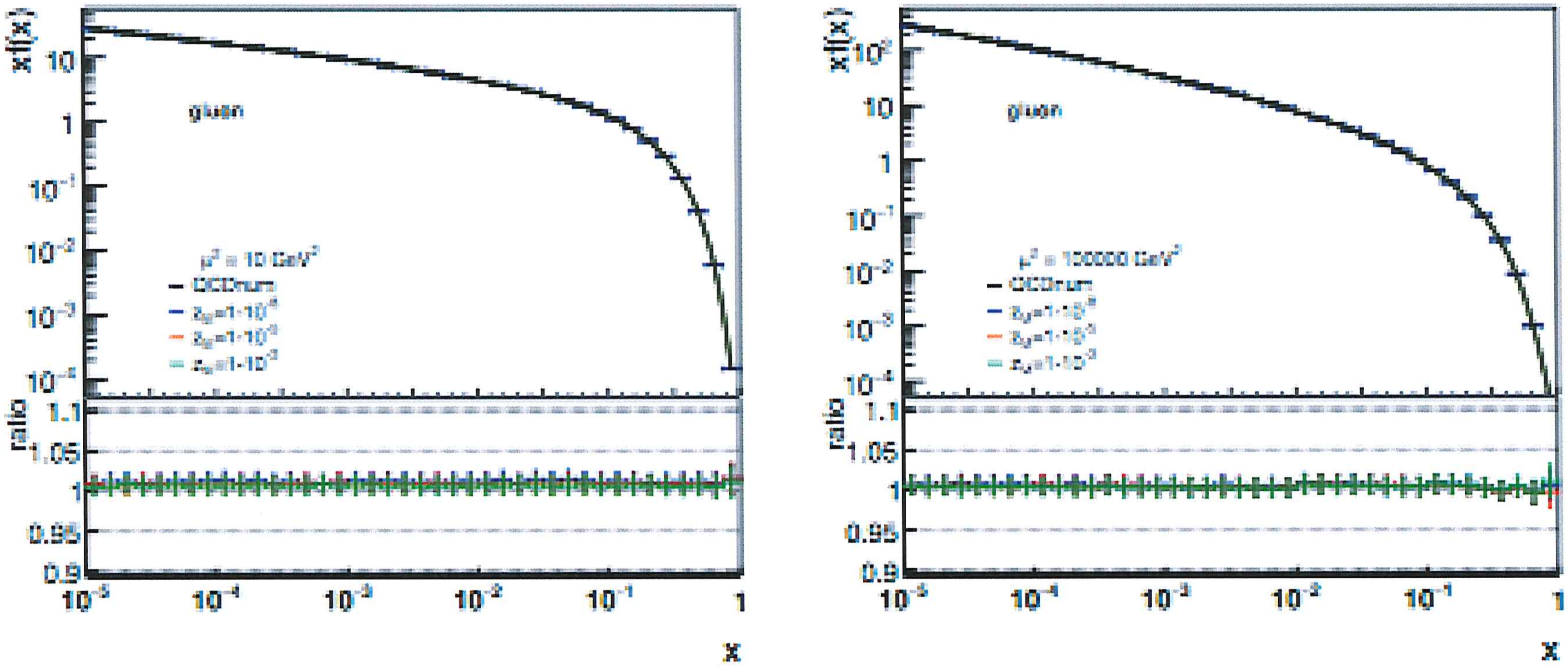


q_t ordering



MULTIPLE SOFT EMISSIONS ARE CORRECTLY TAKEN INTO ACCOUNT BY ANGULAR ORDERING (NOT BY q_t ORDERING)

DISTRIBUTION INTEGRATED OVER k_t



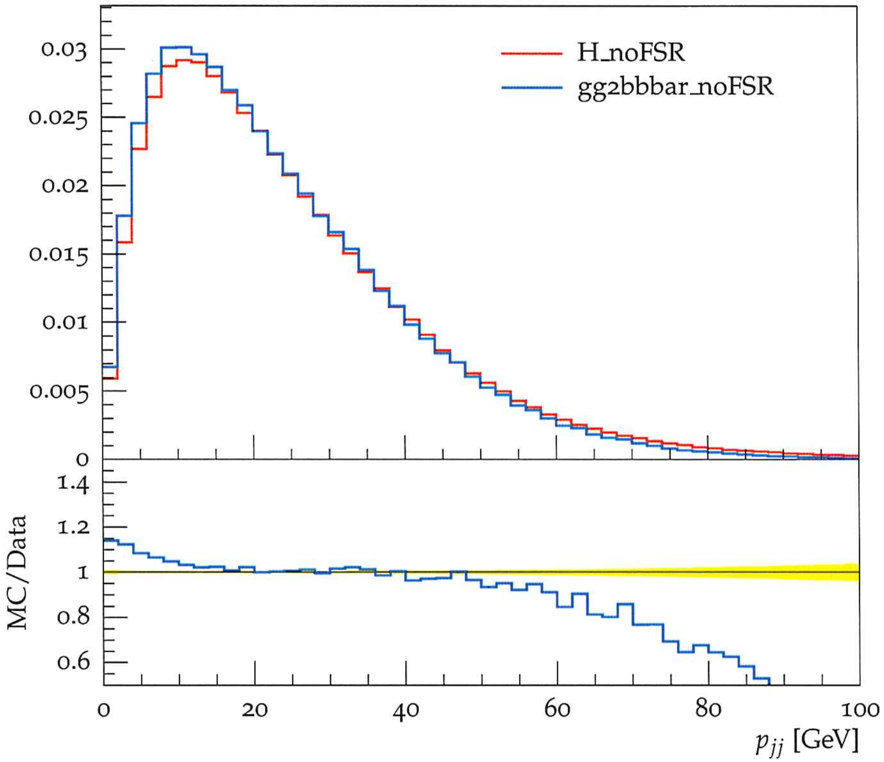
z_M - INDEPENDENCE OBTAINED FOR INTEGRATED DISTRIBUTIONS (REGARDLESS OF ORDERING VARIABLE)

COLOR SINGLET SCENARIOS VERSUS HEAVY QUARKS AND JETS

(*) TO ANALYZE INITIAL-STATE / FINAL-STATE COLOR CORRELATIONS, A PROGRAM OF MEASUREMENTS COULD BE DEVISED, INVOLVING COLOR-SINGLET PROBES ALONG WITH HEAVY FLAVORS AND JETS.

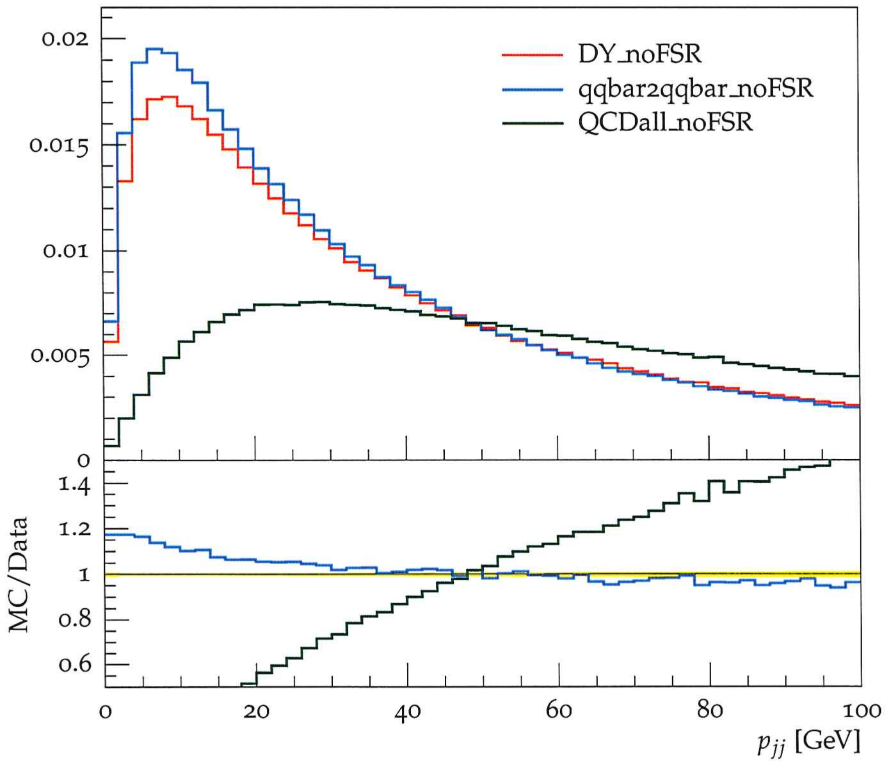
EXAMPLES:

- $b\bar{b}$ vs. Higgs spectra at invariant masses $\sim \mathcal{O}(m_H)$
- jj vs. Drell-Yan at high mass $\sim \mathcal{O}(1\ \mathrm{TeV})$



$b\bar{b}$ versus Higgs

at same invariant mass



(22)

Drell-Yan versus jj

900 GeV < m < 1100 GeV

CONCLUSION

- HIGH-MASS REGION AFFECTED BY POTENTIALLY SIGNIFICANT CORRECTIONS FROM INITIAL-STATE/FINAL-STATE COLOR CORRELATIONS.
- EFFECTS ARISE BEYOND NLO AND LL.
- STUDIED FOR $t\bar{t}$ BUT PRESENT ALSO IN $b\bar{b}$ AND JETS.
- COLOR SINGLET FINAL STATES HELPFUL TO ANALYZE CORRELATIONS AT FIXED INVARIANT MASS.