Particle and Astroparticle Physics Colloquium
DESY, July 2018

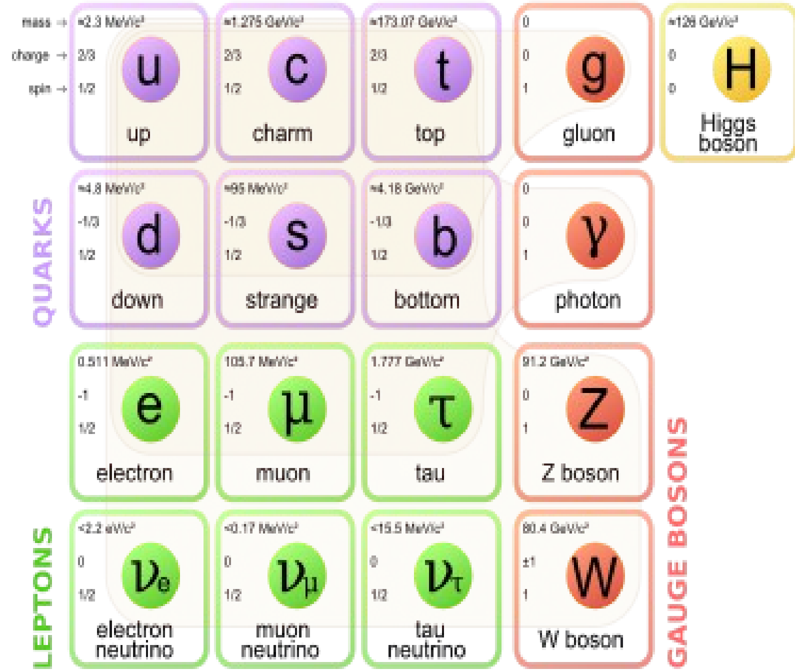
F Hautmann

Soft-Gluon Correlations and TeV Jet Production

- New physics searches and QCD effects
- QCD factorization methods
- Applications to LHC processes

QCD as a part of the Standard Model (SM) of Fundamental Interactions

- Quantum Chromodynamics (QCD), the gauge theory of the strong interaction, is the sector of the SM which is expected to exist as a fundamental theory down to arbitrarily short distances



- On one hand, one relies on QCD to search for new physics in the electroweak sector with high-energy experiments
- On the other hand, one investigates in QCD profound questions probing field theory in “extreme” regions

New physics searches and uses of QCD

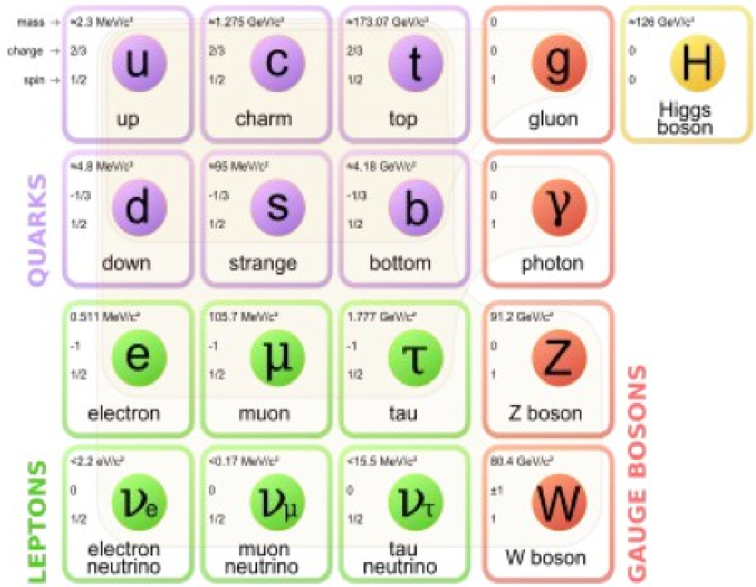
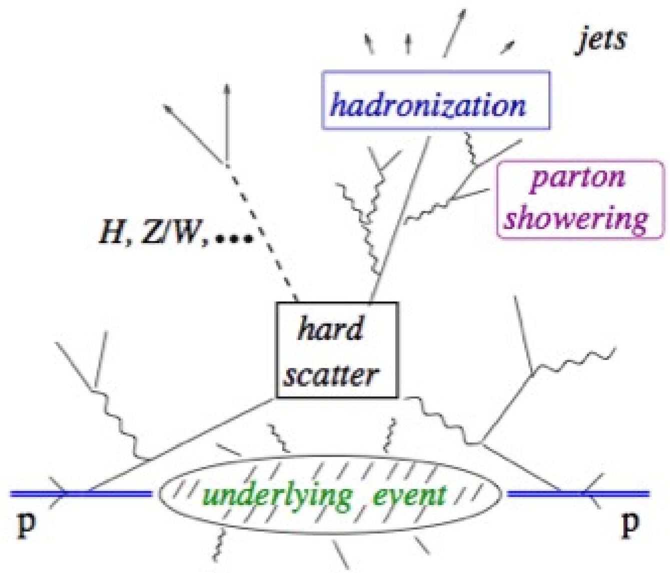


Fig: Building blocks of the SM

- Novel aspects of the SM and potential signals for physics beyond the SM investigated by
  - accelerator experiments such as the LHC and planned future colliders (FCC, EIC, ILC/CLIC)
  - non-accelerator experiments such as astroparticle and cosmic ray experiments: Pierre Auger, IceCube, future neutrino telescopes (KM3Net, …)

- The identification and interpretation of novel physics signals in the complex environments produced in cosmic and collider processes, containing energetic leptons, photons and jets, require a deep knowledge of QCD effects from radiation of “partons” (gluons and quarks), the fundamental quanta of the strongly interacting fields.

LHC pp collision event



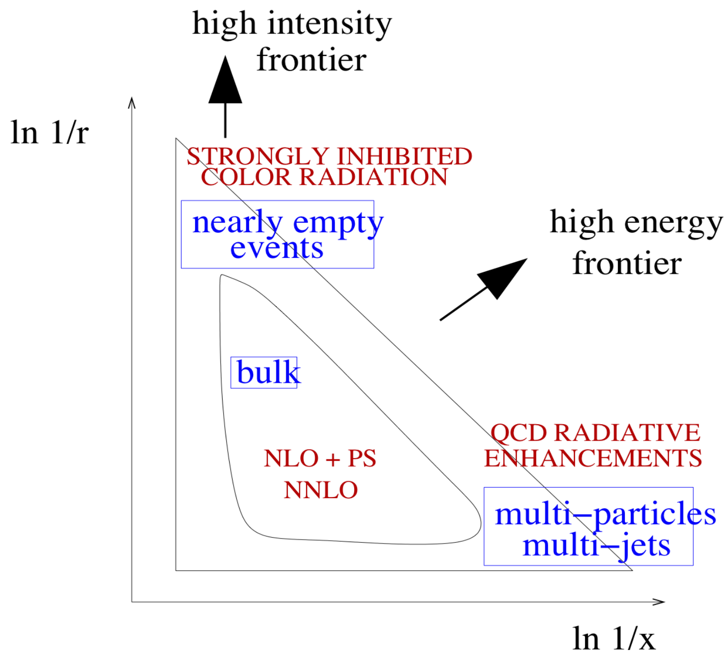
QCD uses an array of techniques to treat high-energy multi-particle production:

- factorization of long-distance dynamics
- perturbative calculat.'s of short-distance processes at fixed order in α_s
- resummation of enhanced radiative corrections to all orders of PT

A cartoon picture of collider's phase space

- New physics probed at distances r ~ 1 / Q
  (Q = hard momentum scale)

- Collision energy $s^{1/2} \sim x^{-1} Q$



Phase space in high-energy hadron collisions

- *Bulk of phase space*
  treatable by methods employed routinely in collider physics: LO, NLO, or NNLO perturbation expansions, matched with "parton-shower" Monte Carlo algorithms
- *Extreme regions near phase space boundary*
  call for cutting-edge factorization and resummation methods which go beyond finite-order perturbation theory

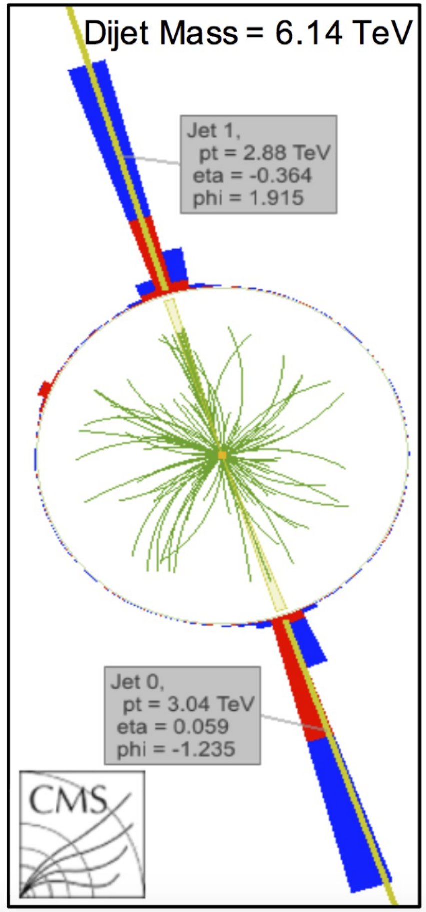
EXAMPLE 1: MULTI-TEV JETS

- Motivated by searches for BSM states and precision physics

- Nearly back-to-back kinematics

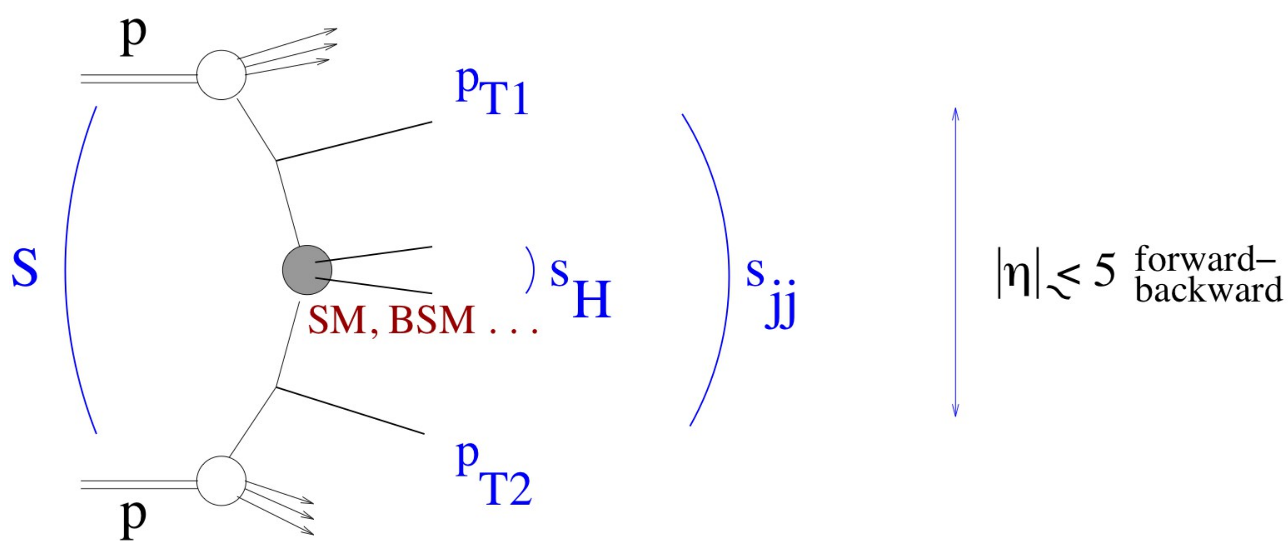
$$\Delta\phi - \pi \approx \mathcal{O}(1 \text{ degree}) \longleftrightarrow \Delta p_T \approx \mathcal{O}(10^2 \text{ GeV})$$

▷ In the back-to-back region, jets are sensitive, despite the high p_T, to infrared QCD effects beyond finite perturbative order (LO, NLO, NNLO ...)

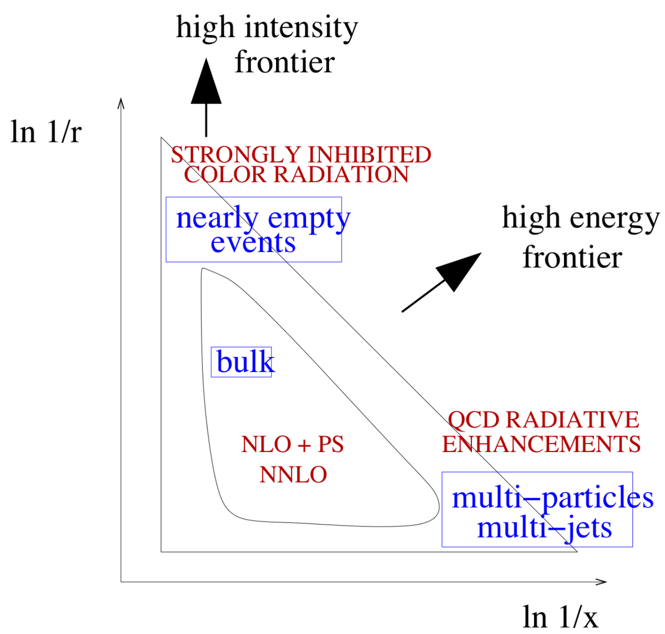


EXAMPLE 2: BOOSTED TOP QUARKS

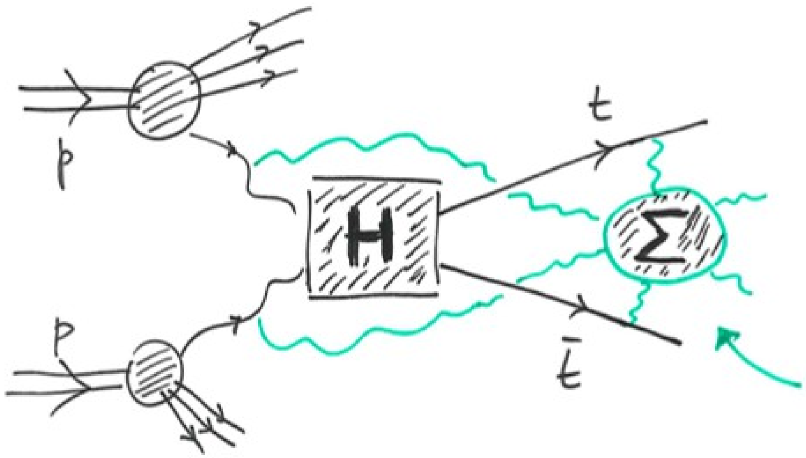
Heavy mass + jets hadro-production



$\longrightarrow$ large range in ratios of sub-energy scales S, s_{jj} and s_H: multiple-scale processes $\longrightarrow$ effects from different sectors in phase space diagram become important



Color correlations in jet and heavy-flavor production in the multi-TeV region



- Initial state / final state soft-gluon correlations $\rightarrow$ new "color entanglement" effects?

- Do such terms contribute beyond NLO and LL?

- To what extent do they affect the region $M_{\mathrm{t\bar{t}}} \gg \Delta p^{\perp}_{\mathrm{t\bar{t}}}$

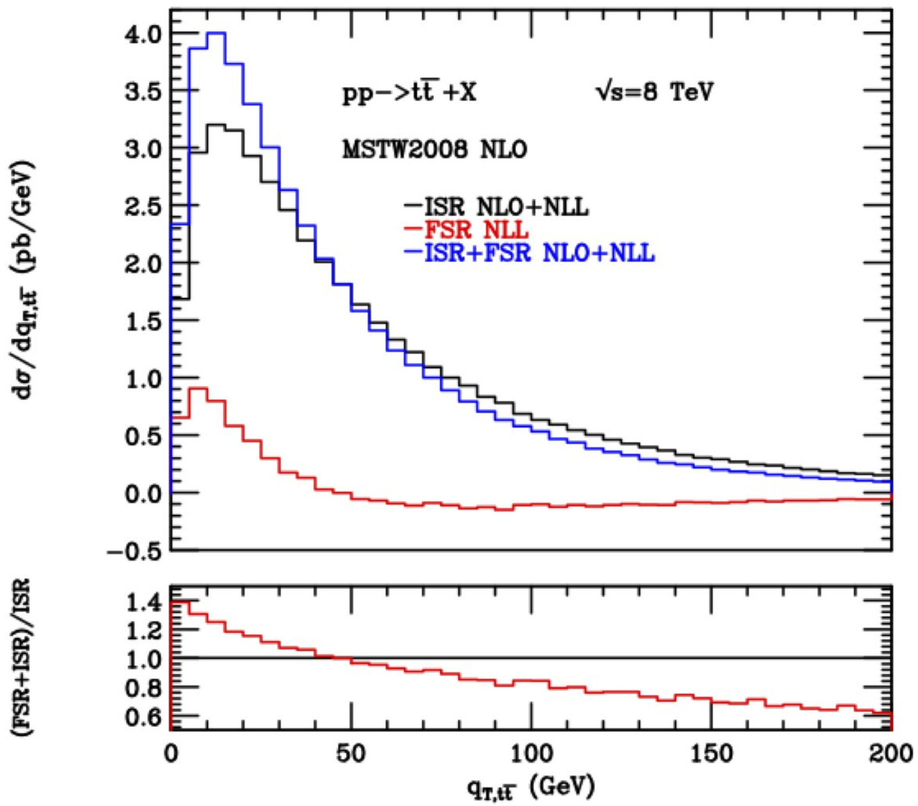
- Significant corrections in $\alpha_S^m \ \ln^k \left(M / \Delta p^{\perp} \right) , \ k \leq 2m$ for any *m*?

Top quark pair production: transverse momentum spectrum

Preliminary results at NLO+NLL

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

H. Sargsyan, talk at CERN, January 2017



Catani, Grazzini,Sargsyan
JHEP 1706 (2017) 017

REMARK

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

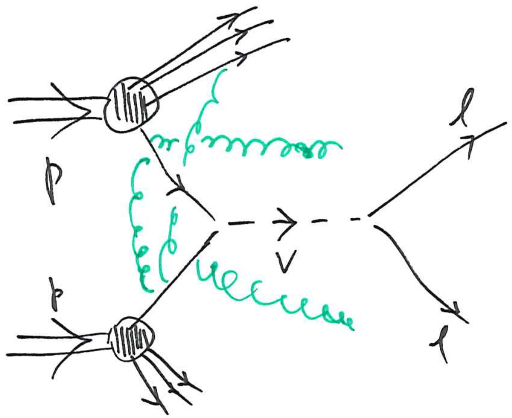
HOW TO SHARPEN ANALYSIS OF CORRELATIONS?

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

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

THE DRELL-YAN CASE

(NO COLOR CORRELATIONS)



- FACTOR MULTIPLE GLUON EMISSIONS IN TRANSVERSE b SPACE:

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

- PREDICT CROSS SECTION AS

"hard"

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

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

TMD pdf's

WHERE

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

COLLINS-SOPER-STERMAN EVOLUTION EQUATIONS

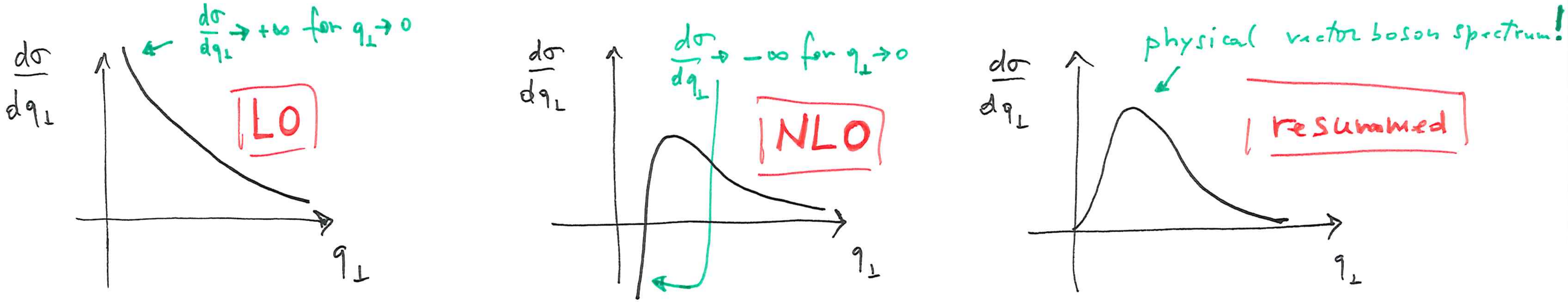
AND

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

(γ_f, γ_K: calculable as a perturbation series)

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

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



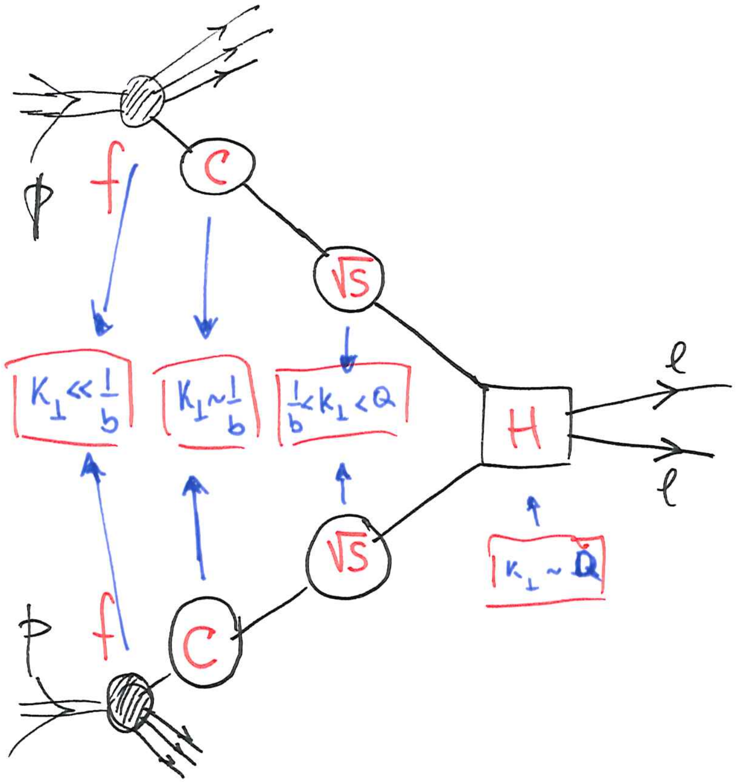
NOTE: SHOWER MONTE CARLO GENERATORS DO THIS "EFFECTIVELY"

- 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



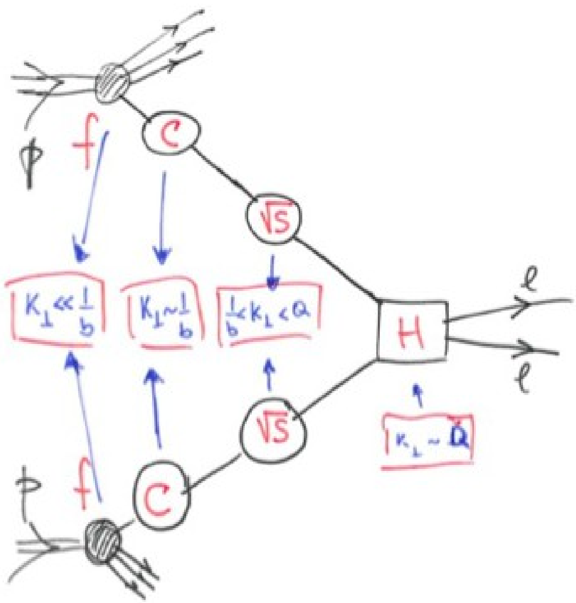
$$\Downarrow$$

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

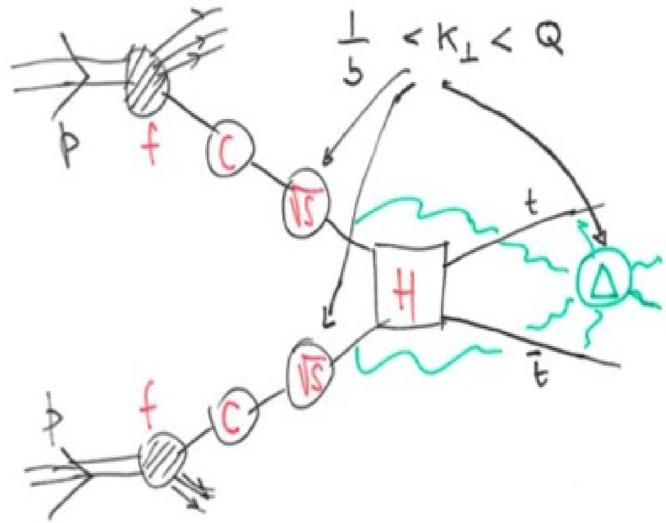
$$\cdot H_{ij}\, C_{ia_1}(z_1)\, C_{ja_2}(z_2)\, f_{a_1}\!\left(\frac{x_1}{z_1},\mu\right) f_{a_2}\!\left(\frac{x_2}{z_2},\mu\right)$$

From color-neutral to color-charged final states

Color neutral:



Color charged:



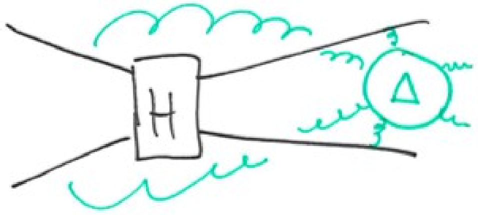
- New long-time correlations in color-charged case:

$$\left(\frac{d\sigma}{d^4 q}\right)_{t\bar{t}} = \sum_{ija_1a_2} \int d^2 b_\perp \; e^{iq_\perp \cdot b_\perp} \; \int dz_1 \int dz_2 \; f_{a_1} \otimes [\mathrm{Tr}(H\Delta)C_1 C_2]_{ija_1a_2} \otimes f_{a_2}$$

soft gluons coupling initial and final states

- Observable at high momentum scales?

STRUCTURE OF SOFT RADIATIVE FACTOR



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

"COLOR ENTANGLEMENT"

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

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

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

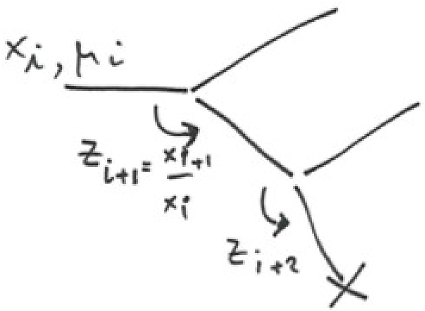
$\Rightarrow$ AZIMUTHAL CORRELATIONS

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

How to compare resummed and parton-shower calculations?

Parton Branching Formulation:

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

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

VALID AT ANY LOOP ORDER

D_{ab}, K_{ab}: flavor diagonal

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

R_{ab}: log terms in $\ln(1-z)$ & analytic terms for $z \to 1$

(*) INTRODUCE RESOLUTION SCALE PARAMETER z_M

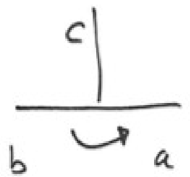
$1 - z_M \sim \mathcal{O}(Q_0^2/Q^2)$; $z > z_M$: "non-resolvable" branchings

Sudakov form factor

$$\tilde f_a(x,\mu^2) = \tilde f_a(x,\mu_0^2)\, S_a(\mu^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{S_a(\mu^2)}{S_a(\mu'^2)} \int_x^{z_M} dz \cdot \left[K_{ab}(\alpha_s(\mu'^2)) \frac{1}{1-z} + R_{ab}(\alpha_s(\mu'^2), z) \right] \tilde f_b(x/z, \mu'^2)$$

real-emission evolution kernel

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



$z = \frac{x_a}{x_b}$

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

$\Rightarrow \; q_c^{\perp 2} = (1-z)\, \mu^2$ "angular ordering"

INITIAL STATE SHOWERS
qT recoils and transverse momentum dependence

$$\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu^2) = S_a(\mu^2)\,\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu_0^2) + \sum_b \int \frac{d^2\mathbf{q}'}{\pi\mathbf{q}'^2}\,\frac{S_a(\mu^2)}{S_a(\mathbf{q}'^2)}\,\Theta(\mu^2-\mathbf{q}'^2)\,\Theta(\mathbf{q}'^2-\mu_0^2)$$

$$\times \int_x^{z_M} dz\, P_{ab}^{(R)}(\alpha_s(\mathbf{q}'^2),z)\,\widetilde{\mathcal{A}}_b(x/z,\mathbf{k}+(1-z)\mathbf{q}',\mathbf{q}'^2)$$

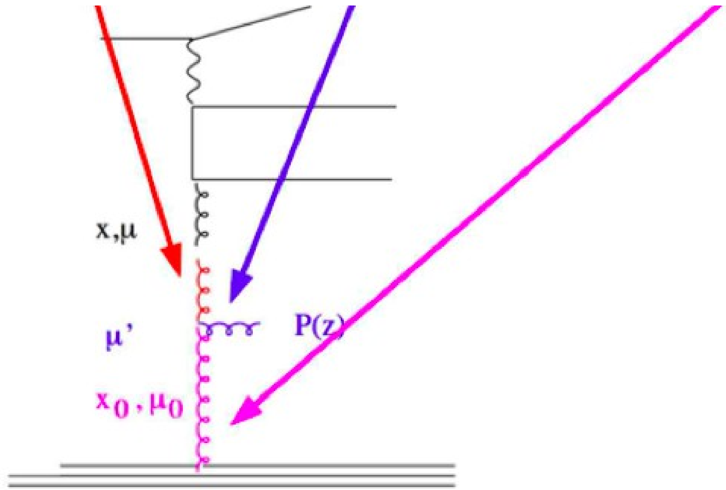
Solve iteratively : $\widetilde{\mathcal{A}}_a^{(0)}(x,\mathbf{k},\mu^2) = S_a(\mu^2)\,\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu_0^2)$, where $S_a(z_M,\mu^2,\mu_0^2) = \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} dz\; z\; P_{ba}^{(R)}(\alpha_s(\mu'^2),z)\right)$

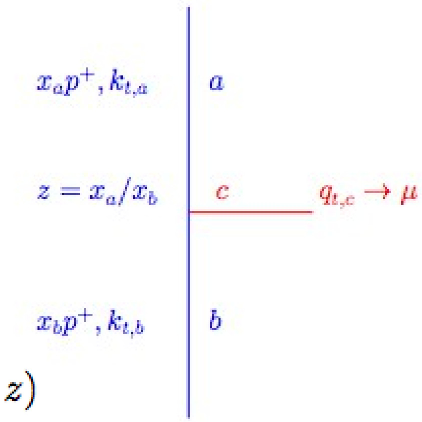
$$\widetilde{\mathcal{A}}_a^{(1)}(x,\mathbf{k},\mu^2) = \sum_b \int \frac{d^2\mathbf{q}'}{\pi\mathbf{q}'^2}\,\Theta(\mu^2-\mathbf{q}'^2)\,\Theta(\mathbf{q}'^2-\mu_0^2)$$

$$\times\ \frac{S_a(\mu^2)}{S_a(\mathbf{q}'^2)} \int_x^{z_M} dz\, P_{ab}^{(R)}(\alpha_s(\mathbf{q}'^2),z)\,\widetilde{\mathcal{A}}_b(x/z,\mathbf{k}+(1-z)\mathbf{q}',\mu_0^2)\; S_b(\mathbf{q}'^2)$$

↖ NB: angular ordering

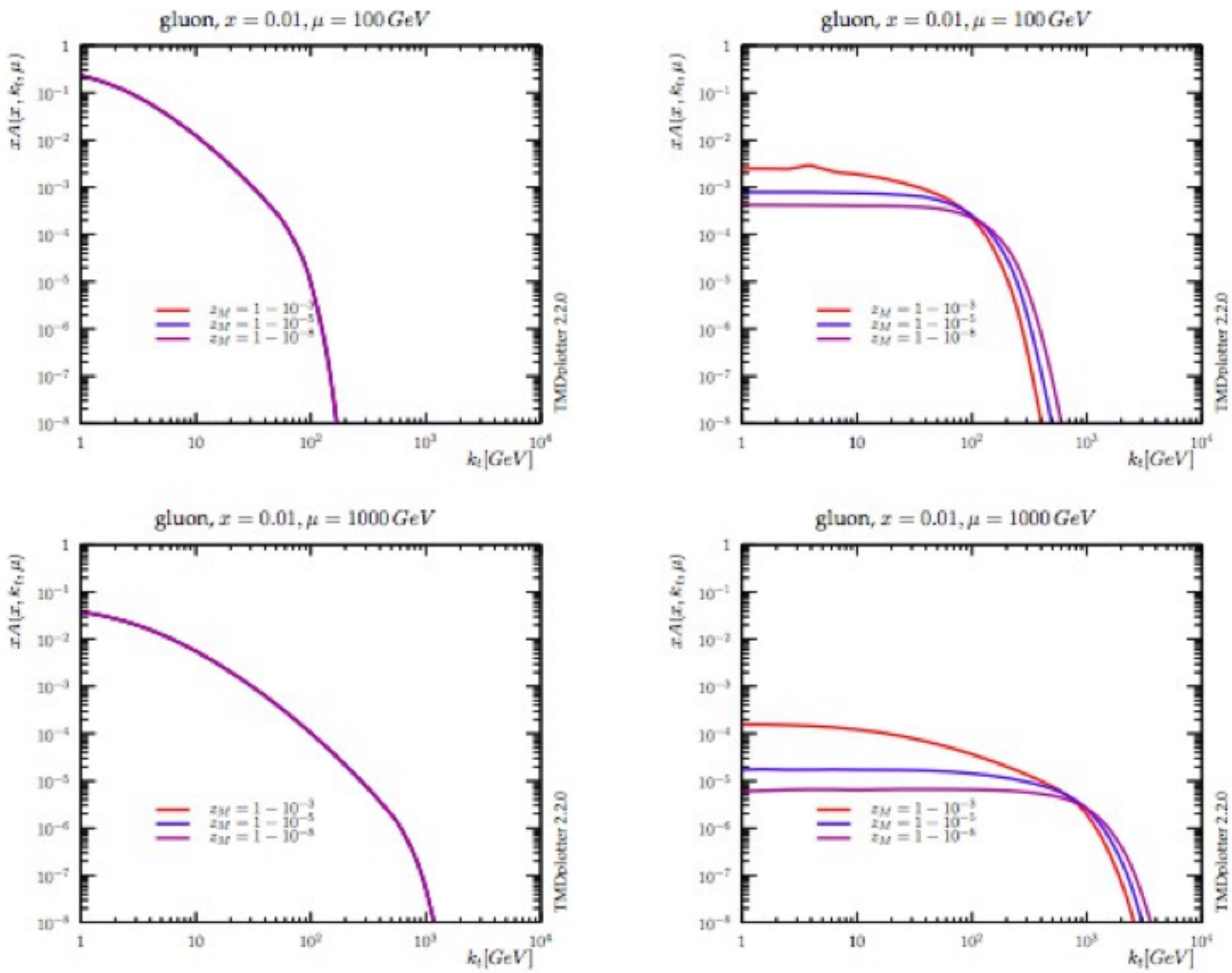
Jung, Lelek, Radescu, Zlebcik & H, JHEP 01 (2018) 070





$\mu = |\mathbf{q}_c|/(1-z)$

TMDs and soft-gluon resolution effects



angular ordering

transverse momentum ordering

Well-defined TMDs require appropriate ordering condition

Parton branching method in xFitter

- Determine starting distribution

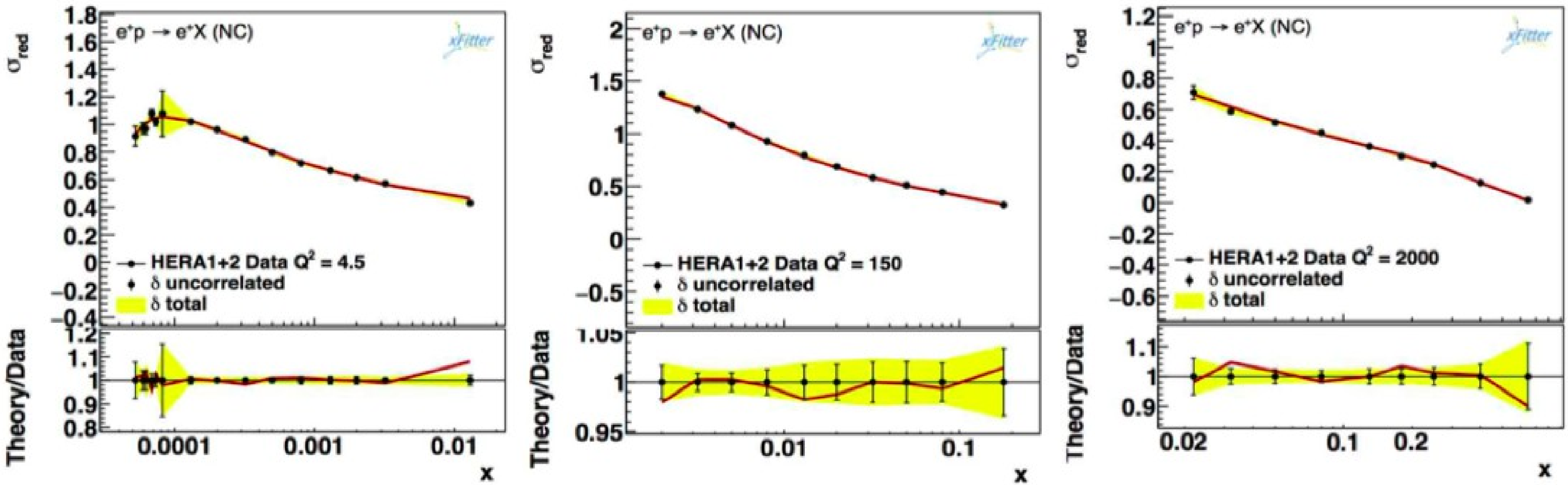
A Bermudez et al, arXiv:1804.11152

A. Lelek et al REF 2016

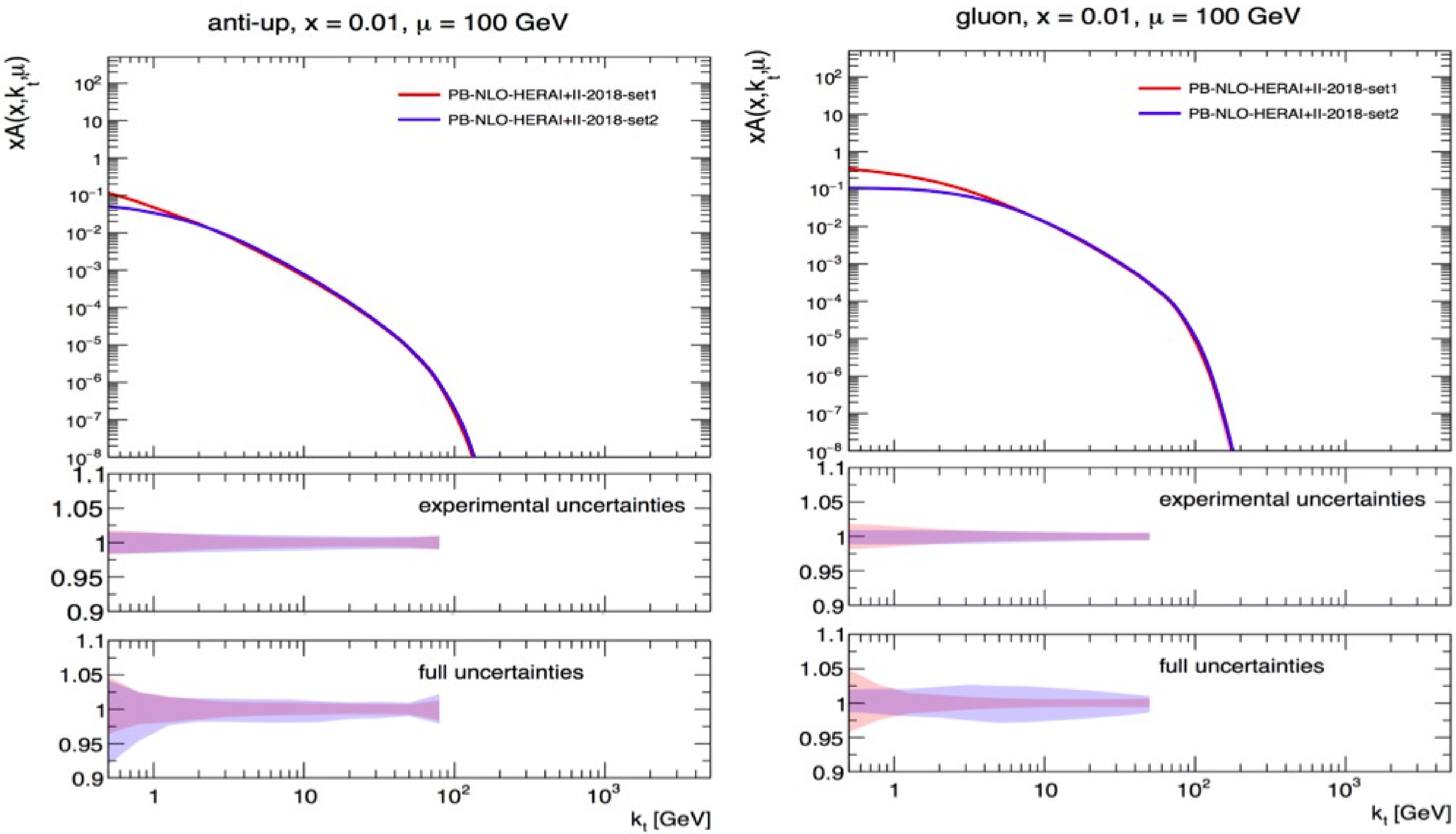
$$xf_a(x,\mu^2) = x\int dx' \int dx'' \mathcal{A}_{0,b}(x')\tilde{\mathcal{A}}_a^b\left(x'',\mu^2\right)\delta(x'x''-x)$$

$$= \int dx' \mathcal{A}_{0,b}(x')\cdot\frac{x}{x'}\,\tilde{\mathcal{A}}_a^b\left(\frac{x}{x'},\mu^2\right)$$

- fit to HERA data (using xFitter) with $Q^2 \geq 3.5$ GeV² gives $\chi^2/ndf \sim 1.2$



TMD distributions from fit to HERA data



A Bermudez et al, arXiv:1804.11152

- NLO determination of TMDs with uncertainties

CURRENT WORK

- Drell-Yan pT spectrum from convolution of two transverse momentum dependent distributions
- Comparison of parton branching results with analytic TMD resummation (Collins-Soper-Sterman method)
- First implementation for jets (using NLO matrix elements for color-charged final states)

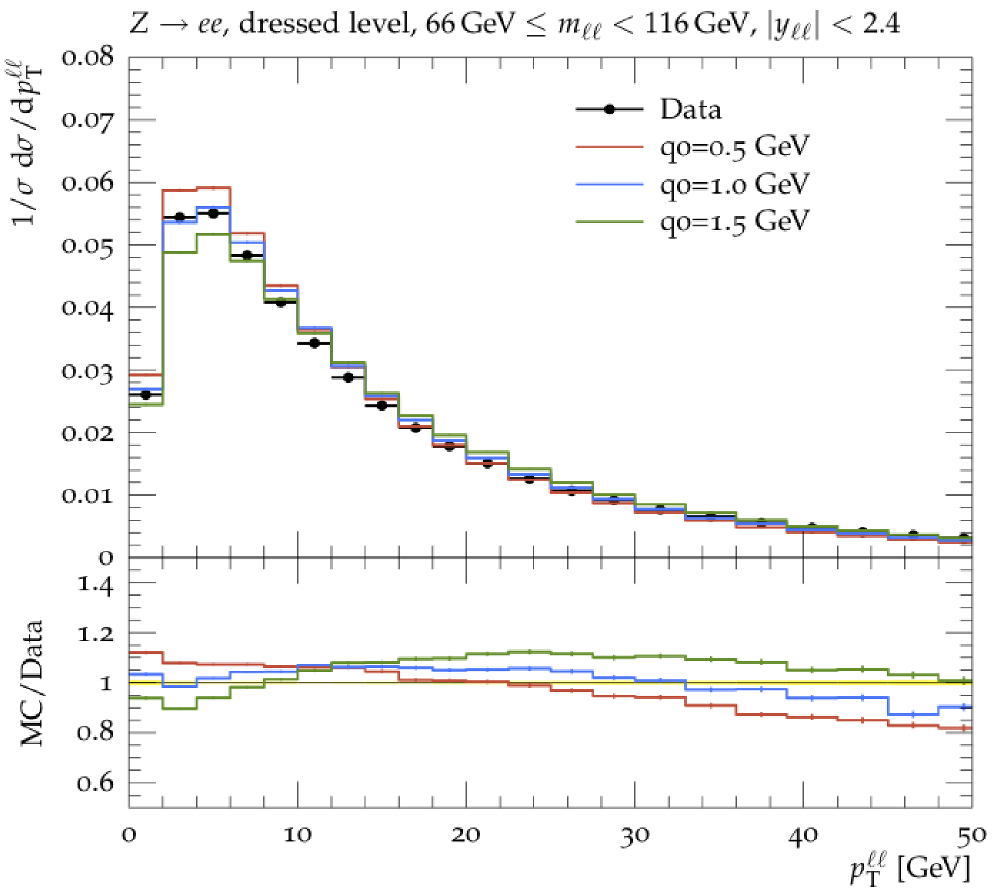
Angular ordering and soft-gluon resolution effects in Z-boson pT spectrum

- Parton branching TMD defined by using angular ordering
  - Scale in running coupling also by angular ordering

$$\alpha_s(\mu^2(1-z)^2)$$

- mu-dependent soft-gluon resolution scale parameter zM

$$z_M(\mu) = 1 - q_0/\mu$$



LHC Electroweak WG Meeting, CERN, June 2018

COMPARISON WITH TMD (COLLINS-SOPER-STERMAN) RESUMMATION

◇ The resummed DY differential cross section is given by

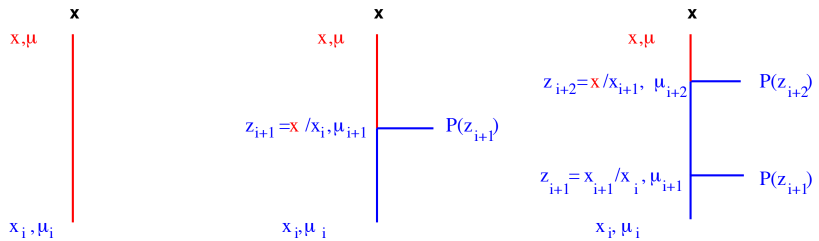
$$\frac{d\sigma}{d^2\mathbf{q}dM^2dy} = \sum_{q,\bar{q}} \frac{\sigma^{(0)}}{s} H(\alpha_{\rm S}) \int \frac{d^2\mathbf{b}}{(2\pi)^2}\; e^{i\mathbf{q}\cdot\mathbf{b}} \mathcal{A}_q(x_1, \mathbf{b}, M) \mathcal{A}_{\bar{q}}(x_2, \mathbf{b}, M) + \mathcal{O}\left(\frac{|\mathbf{q}|}{M}\right) \quad \text{where}$$

$$\mathcal{A}_i(x, \mathbf{b}, M) \;=\; \exp\left\{ \frac{1}{2} \int_{c_0/b^2}^{M^2} \frac{d\mu'^2}{\mu'^2} \left[A_i(\alpha_{\rm S}(\mu'^2)) \ln\left(\frac{M^2}{\mu'^2}\right) + B_i(\alpha_{\rm S}(\mu'^2)) \right] \right\} \exp\left(\frac{-\mathbf{b}^2}{2\lambda^2}\right)$$

$$\times \quad \sum_j \int_x^1 \frac{dz}{z} C_{ij}\left(z, \alpha_{\rm S}\left(\frac{c_0}{\mathbf{b}^2}\right)\right) f_j\left(\frac{x}{z}, \frac{c_0}{\mathbf{b}^2}\right)$$

and the coefficients H, A, B, C have power series expansions in α_S.

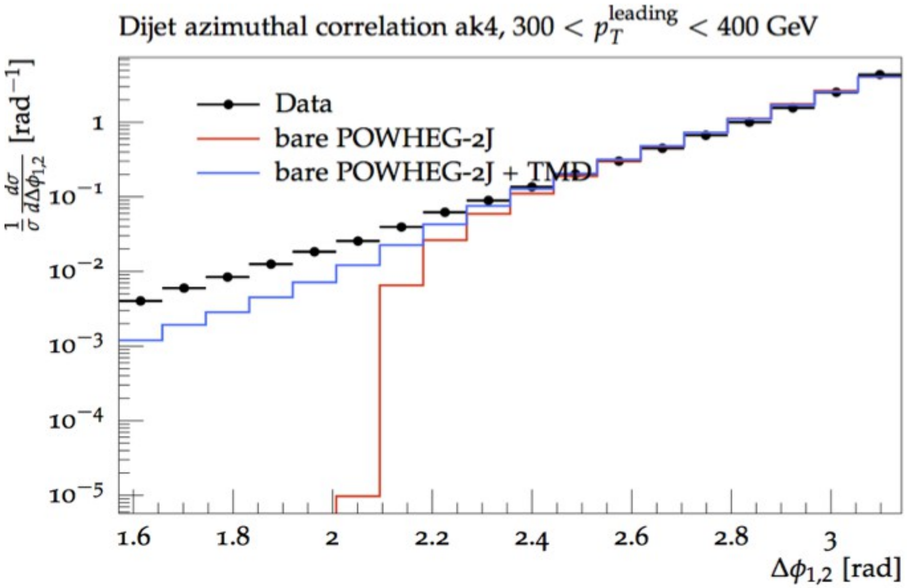
◇ The parton branching TMD is expressed in terms of real-emission $P^{(R)}$:

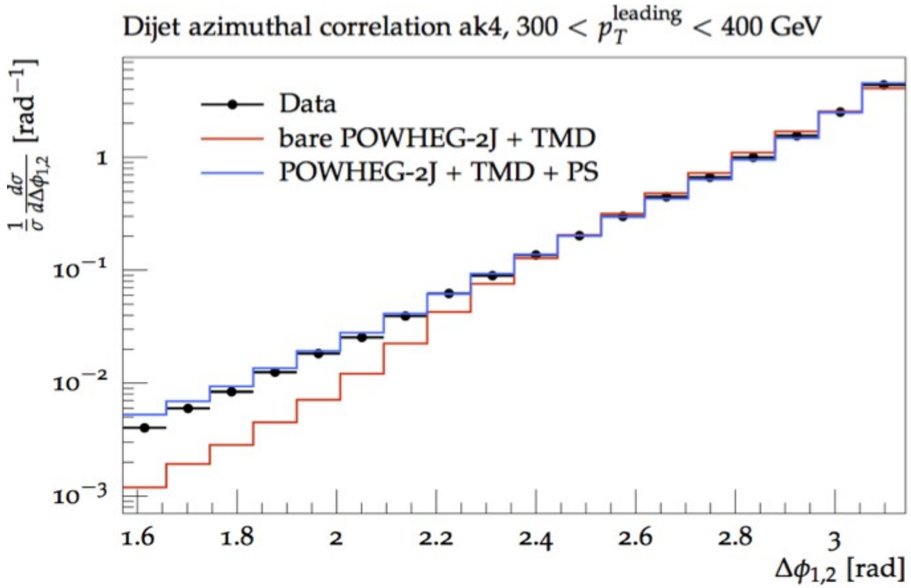


▷ via momentum sum rules, use unitarity to relate $P^{(R)}$ to virtual emission

▷ identify the coefficients in the two formulations, order by order in α_S, at LL, NLL, . . .

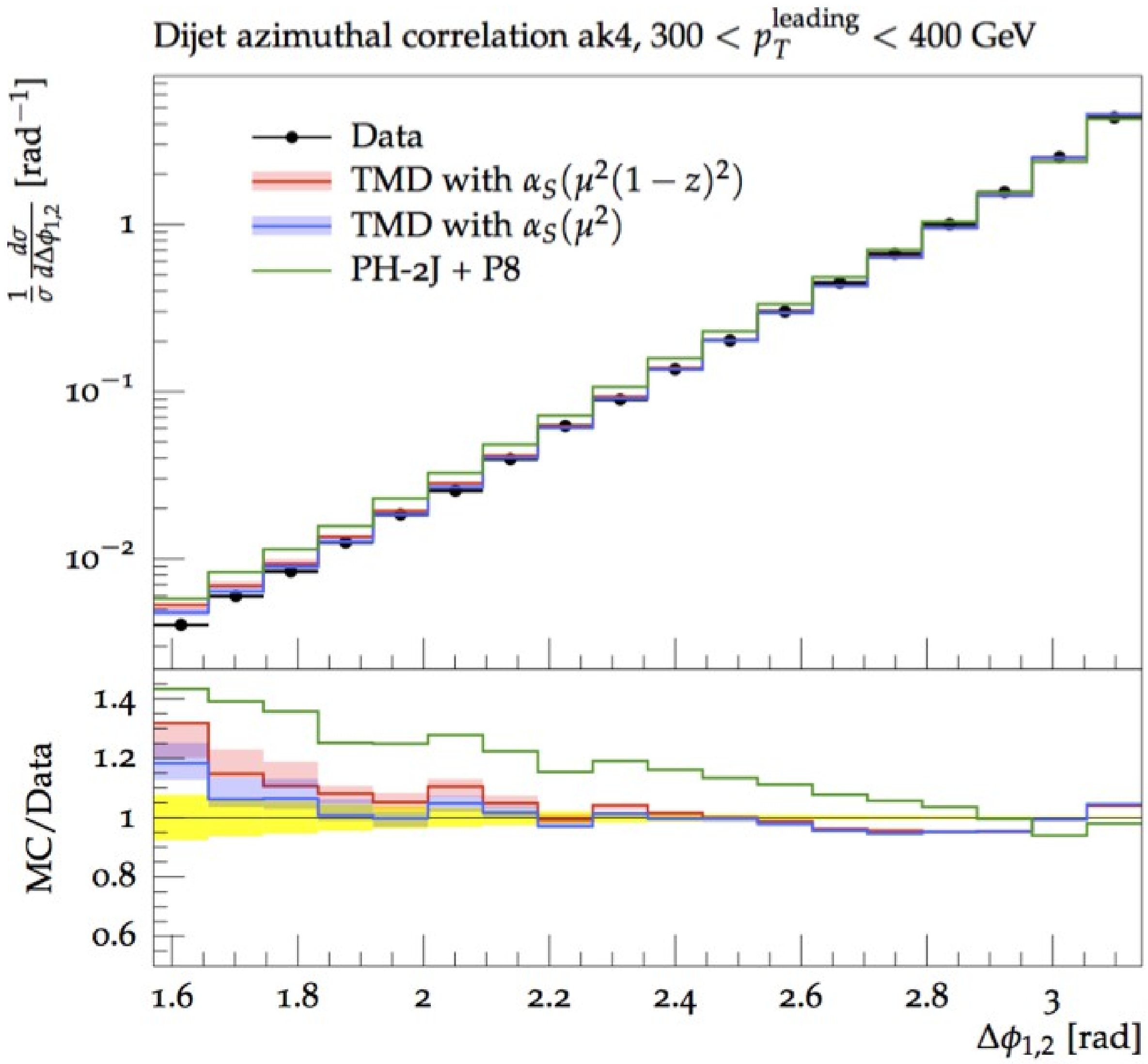
Di-jets from NLOPS with TMDs





- Events by NLO POWHEG 2 jets
- Parton branching TMD (with angular ordering)
- TMD parton shower

Di-jets from NLOPS with TMDs



- Events by NLO POWHEG 2 jets
- Parton branching TMD (with angular ordering)
- TMD parton shower

CONCLUSION

- New physics searches at highest mass and shortest distances depend on chromodynamic effects which probe the structure of the theory beyond finite-order perturbation expansions

    ex.: soft gluon correlations in multi-TeV jet production

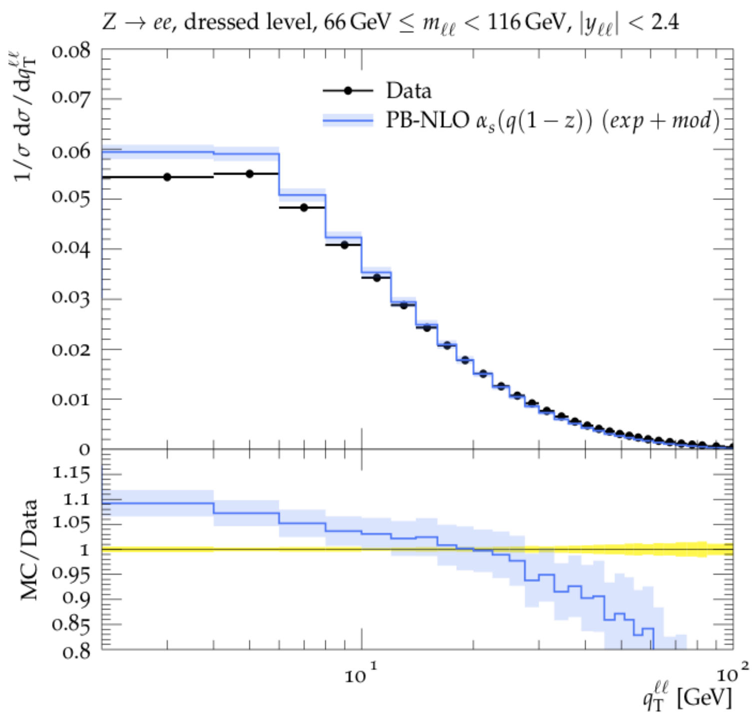
- The Parton Branching method provides a consistent treatment of initial-state distributions, including transverse momentum, and parton showers, valid over a wide range in x, kT, mu:

    first NLO determination of TMDs including uncertainties

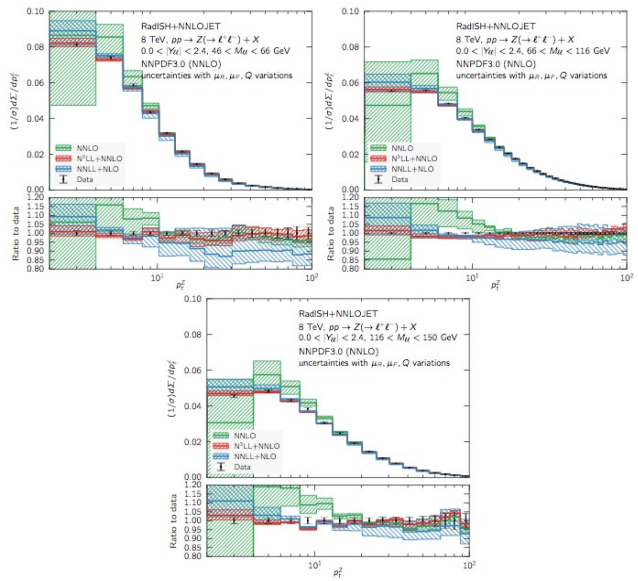
    NLOPS with TMDs

- Opens the way to new approach to make precision predictions and estimate theoretical uncertainties, including showering

Z-boson pT spectrum including TMD uncertainties



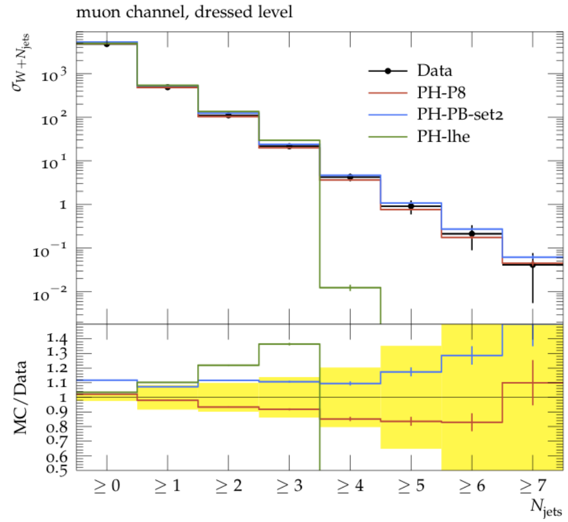
- Cf. predictions from fixed-order + resummed calculations Bizon et al., arXiv:1805.05916

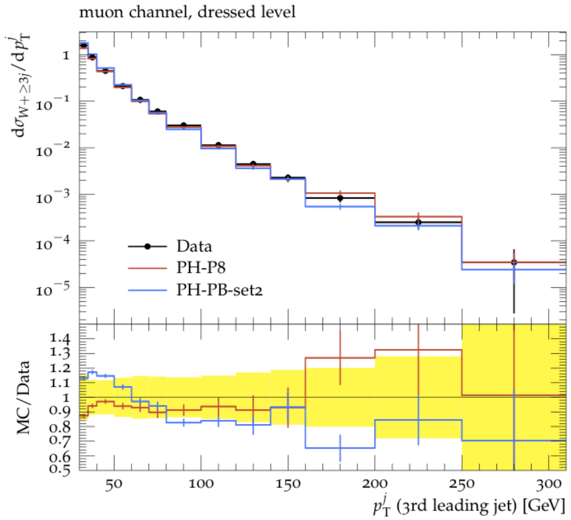


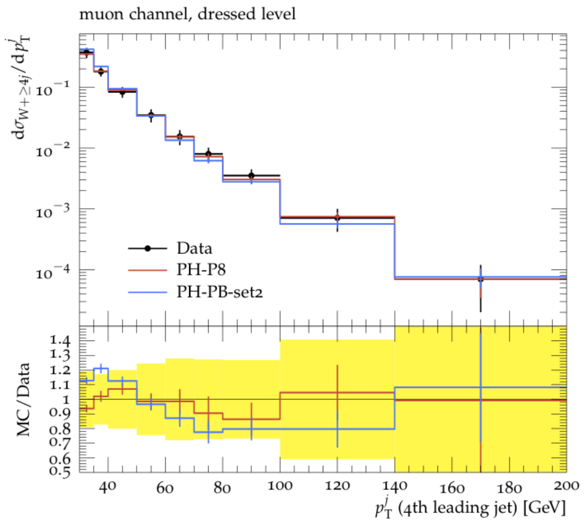
W + n jets from NLOPS with TMD

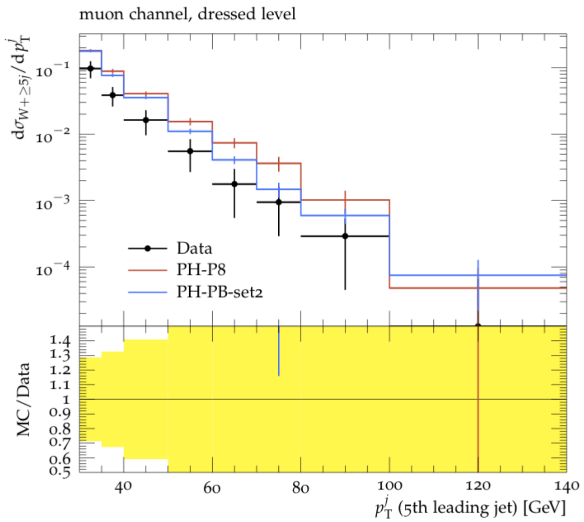
- POWHEG
  NLO W+2 jets

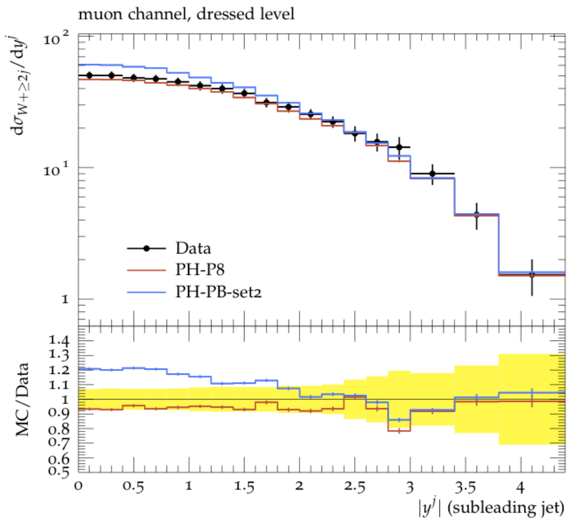
- TMD shower











LHC Electroweak WG Meeting, CERN, June 2018