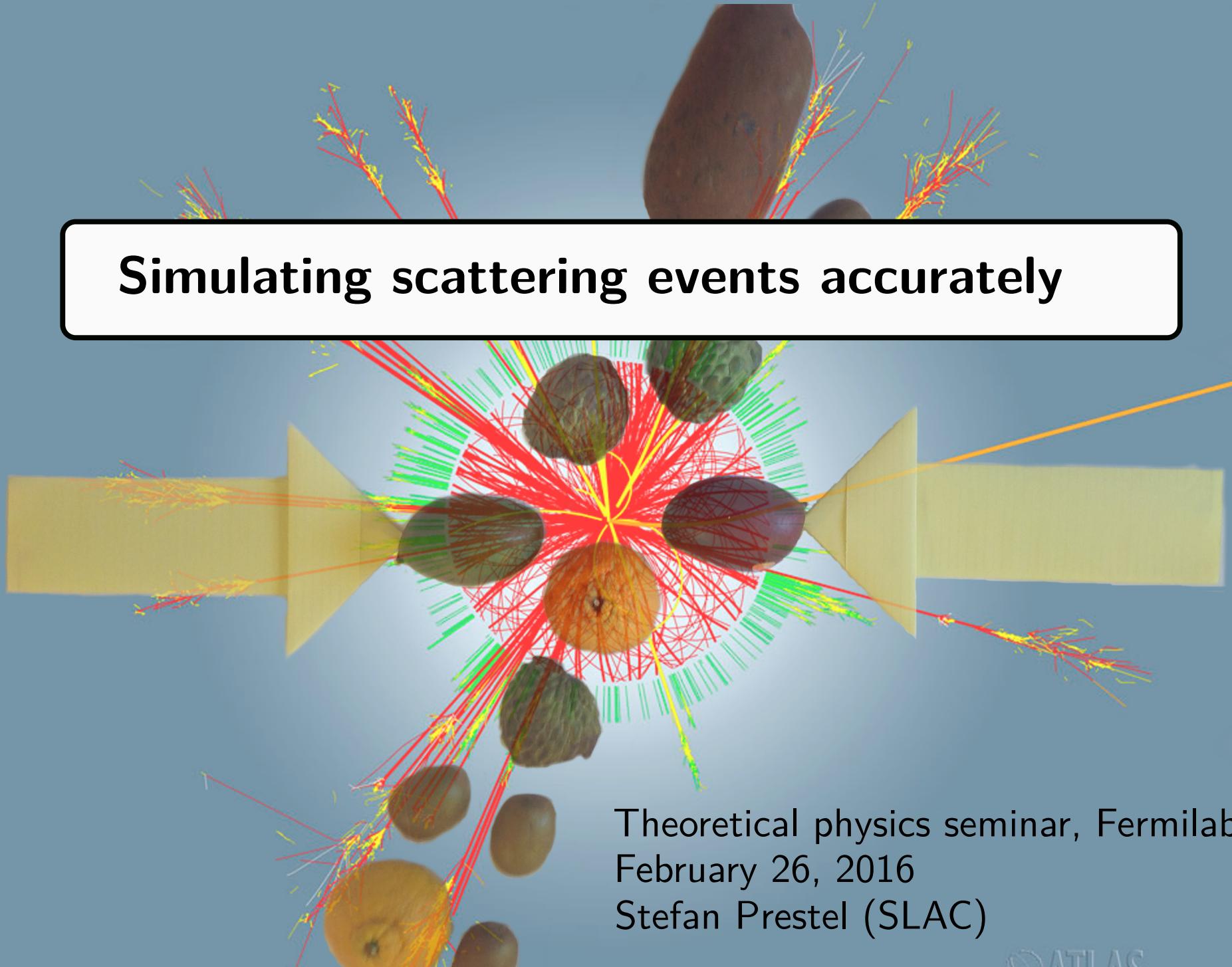
Simulating scattering events accurately



Theoretical physics seminar, Fermilab
February 26, 2016
Stefan Prestel (SLAC)

Outline

1. Motivation
2. Modelling scattering events
3. Perturbative predictions.
4. Summary and Outlook

A biased view of particle physics

We are in the privileged position that we have experiments covering vastly different phenomena:

Low-energy experiments
Hadron structure
Collider experiments
New physics searches
Cosmic ray experiments
Diffraction
Dark matter detection
New physics searches
Neutrino experiments
Hadron and nuclear structure

The phenomena at these experiments can be quite different ...but also very similar!

How will we falsify our theories?

Know what we want to look for...

Smoking guns of classical SUSY, extra dimensions?

Subtle effects if BSM is hidden by compressed spectra?

Kinematic shifts as energy escapes to dark sectors?

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Know what we're facing...

QCD

QCD

...with a dash of Standard Model.

How will we falsify our theories?

Know what we want to look for...

Smoking guns of classical SUSY, extra dimensions?

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Kinematic shifts as energy escapes to dark sectors?

Know what we're facing...

QCD

QCD

...with a dash of Standard Model.

Assess if there is a realistic chance with our current experiments
...and check before building a new experiment.

2. Modelling scattering events

To find new hints of new phenomena, we compare experimental data with our "best" theory.

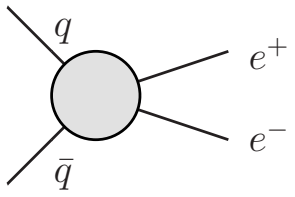
> General Purpose Monte Carlo Event Generators (MCEGs) aim at being repositories for the most accurate theory knowledge.

Common high-energy MCEGs are HERWIG, PYTHIA and SHERPA

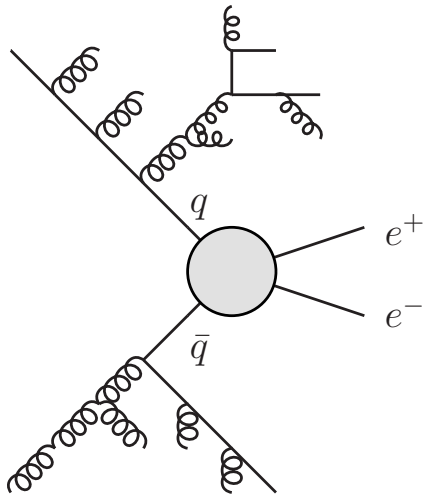
PYTHIA is the most widely used generator.

Accurate simulations are an ambitious task. In the following, I'll focus on how we tackle simulating collider events.

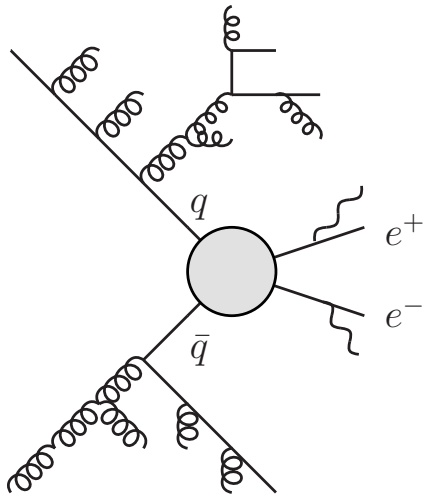
High-energy scattering $ab \to ABC\ldots$ of fundamental particles at the "core" of the collision



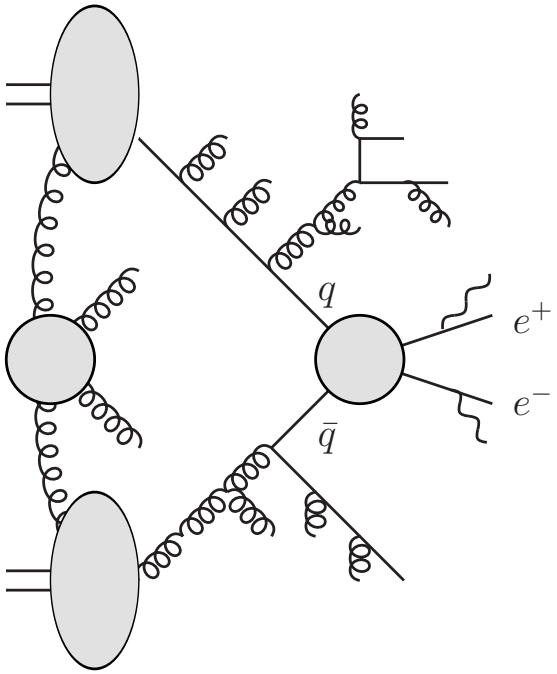
Highly accelerated particles decelerate by radiating (especialy QCD emissions) arbitrarily often,



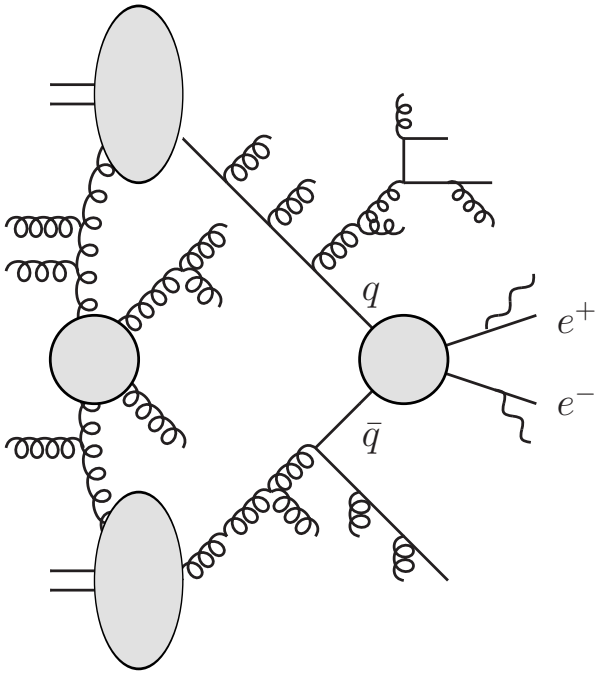
…but even massive W- or Z-bosons can be radiated at very high energies.



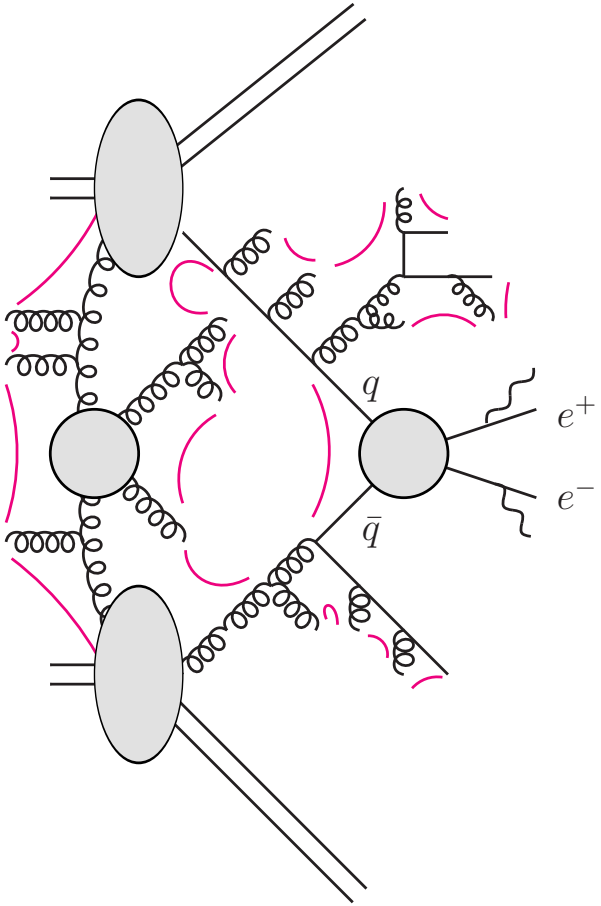
Colliding composite protons means there can be many interactions between the proton constituents



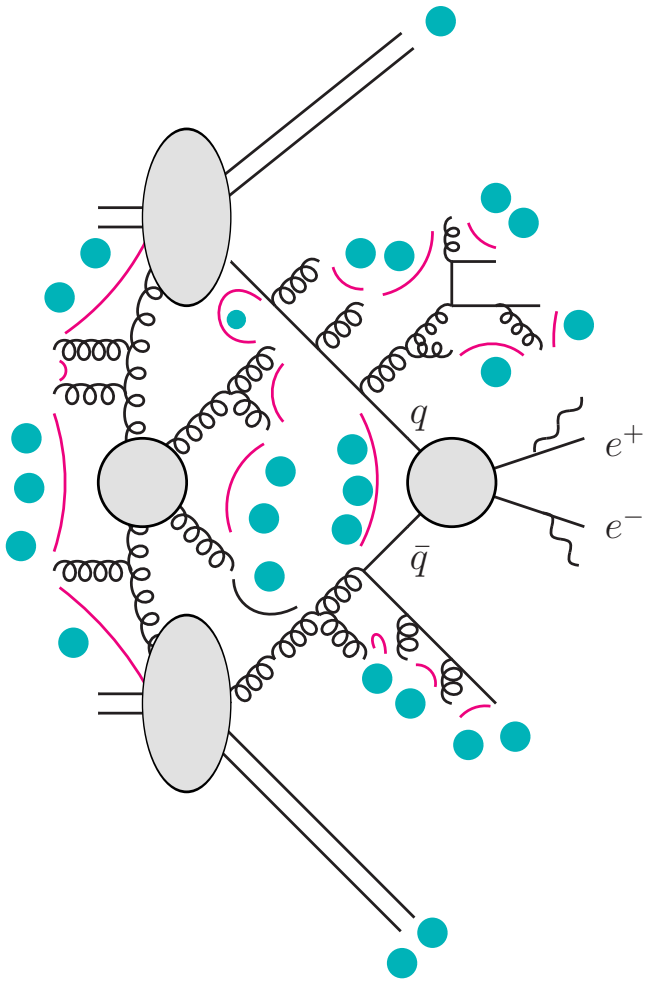
...which all produce yet more radiation.



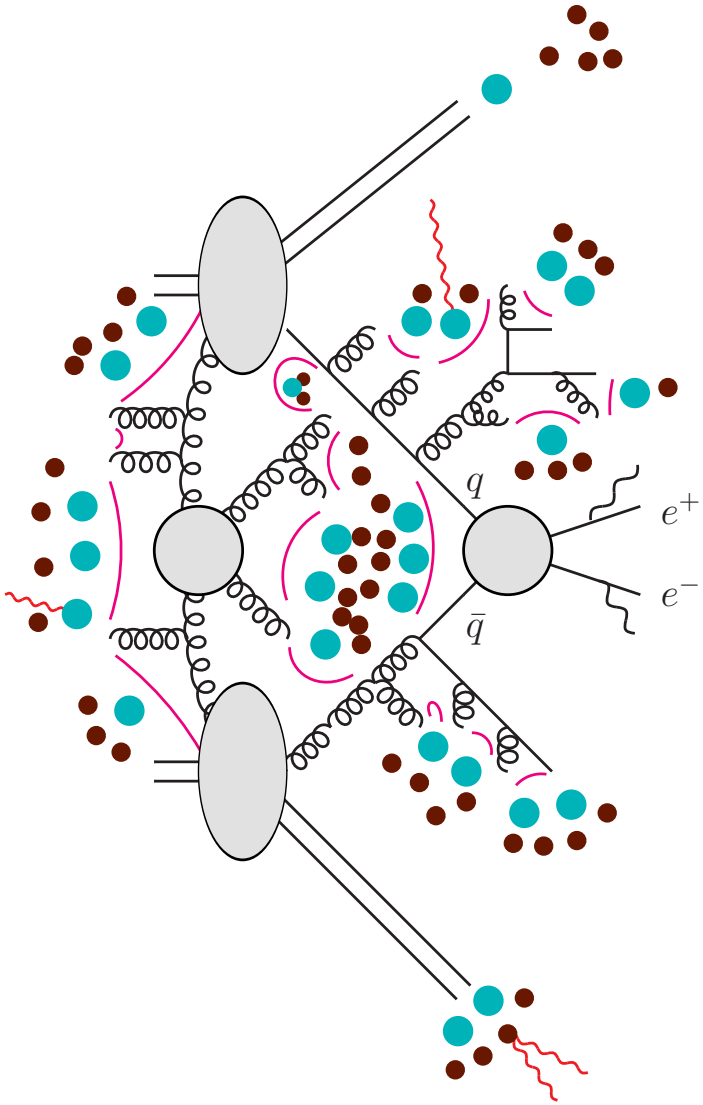
If all energies are small, we have a phase transition to a colour-neutral state (by transitioning to "proto-hadron" colour strings)



The colour-neutral strings then break up into tiny pieces forming (highly excited) hadrons,



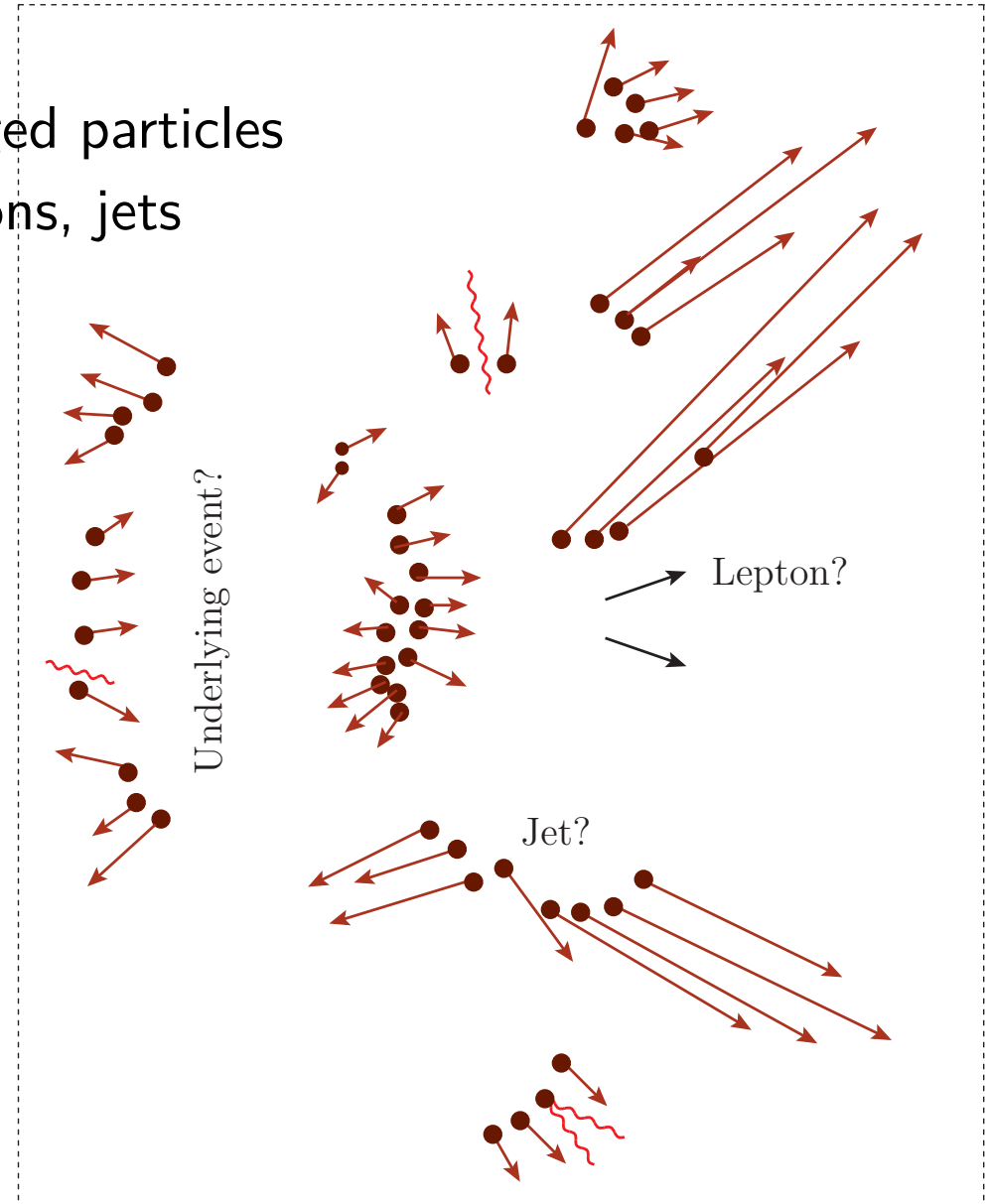
and the excited hadrons decay into the particles (protons, pions, photons, electrons ...) we see in the detector.

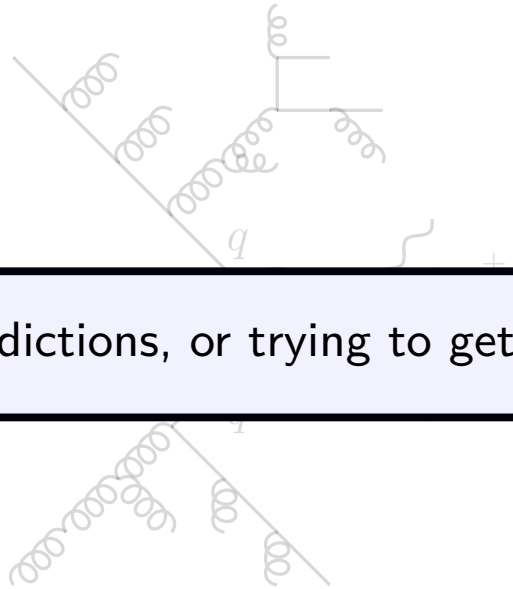


And the detector records this...

$100 - 1000$ charged particles

$+$ photons, leptons, jets



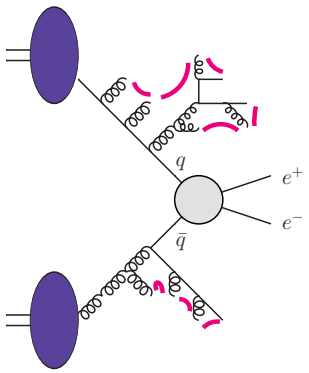


3. Perturbative predictions, or trying to get the hard dynamics right.

Calculations in QCD

To calculate a scattering, we need to factorize long-distance effects from calculable short-distance physics σ.

$$\sigma = \int d\sigma_{(ab\to X+N \text{ partons})}(\text{high energy}) \otimes f_{a\in A}(x_a, \text{high energy}) \otimes f_{b\in B}(x_b, \text{high energy}) \otimes \mathcal{D}(p_1, p_2, \ldots, p_N, p_A, p_B)$$



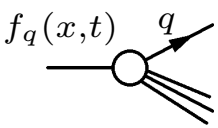
$f(x, \text{energy}) \mathrel{\widehat{=}}$ Probability to find parton with momentum fraction x in hadron, when looking with the "resolution" $1/\text{energy}$

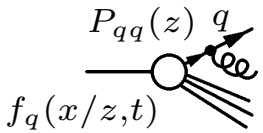
Extract f and $\mathcal{D}$ where perturbation theory not valid (low energy).

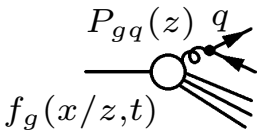
More accurate calculation of perturbative dynamics $\to$ Less impact of parametrization!

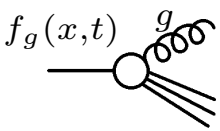
The evolution of distribution functions

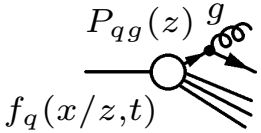
Energy evolution given by DGLAP evolution equations:

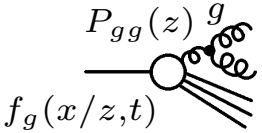
$$\frac{\mathrm{d}}{\mathrm{d}\log(t/\mu^2)}$$ 

$$= \int_x^1 \frac{\mathrm{d}z}{z}\frac{\alpha_s}{2\pi}$$ 

$$+ \int_x^1 \frac{\mathrm{d}z}{z}\frac{\alpha_s}{2\pi}$$ 

$$\frac{\mathrm{d}}{\mathrm{d}\log(t/\mu^2)}$$ 

$$= \sum_{i=1}^{2\,n_f} \int_x^1 \frac{\mathrm{d}z}{z}\frac{\alpha_s}{2\pi}$$ 

$$+ \int_x^1 \frac{\mathrm{d}z}{z}\frac{\alpha_s}{2\pi}$$ 

$\Rightarrow$ When increasing the resolution, we can

a) still find the same parton, or

b) find that the parton came from decay of large-momentum parton.

Both a) and b) have perturbatively calculable probabilities!

The parton shower cascade

$$\int_t^\mu \frac{d\bar{t}}{\bar{t}} \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) \quad \equiv$$

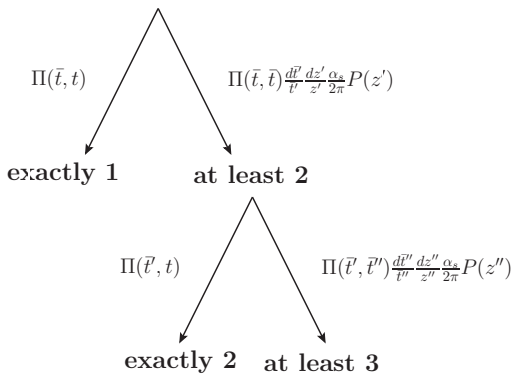
Probability of a resolvable emission in the range $[\mu, t]$.

$$\Pi_n(\mu, t) = \exp\left(- \int_t^\mu \frac{d\bar{t}}{\bar{t}} \int \frac{dz}{z} \frac{\alpha_s}{2\pi} \right) \quad \equiv$$

Probability of no resolvable emission in the range $[\mu, t]$.

By changing the resolution from $\mu \to t$, the cross section B changes to

$$\mathrm{B} \quad \to \quad \underbrace{\mathrm{B}_0 \Pi(\mu, t)}_{\textbf{no emission}} \; + \; \underbrace{\mathrm{B} \int_t^\mu \frac{d\bar{t}}{\bar{t}} \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) \Pi(\mu, \bar{t})}_{\textbf{at least 1 emission}} \; + \; \ldots$$



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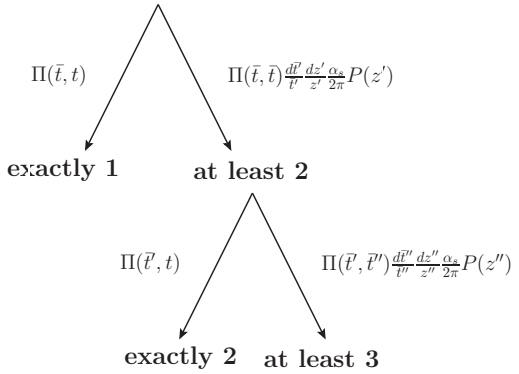

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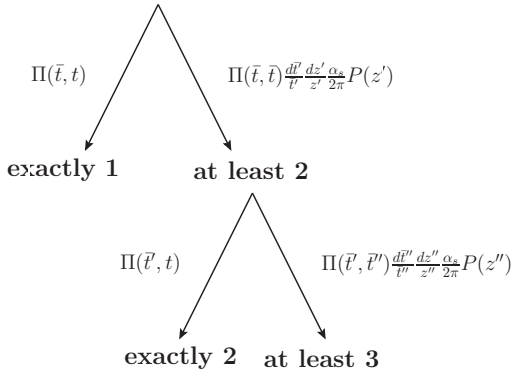
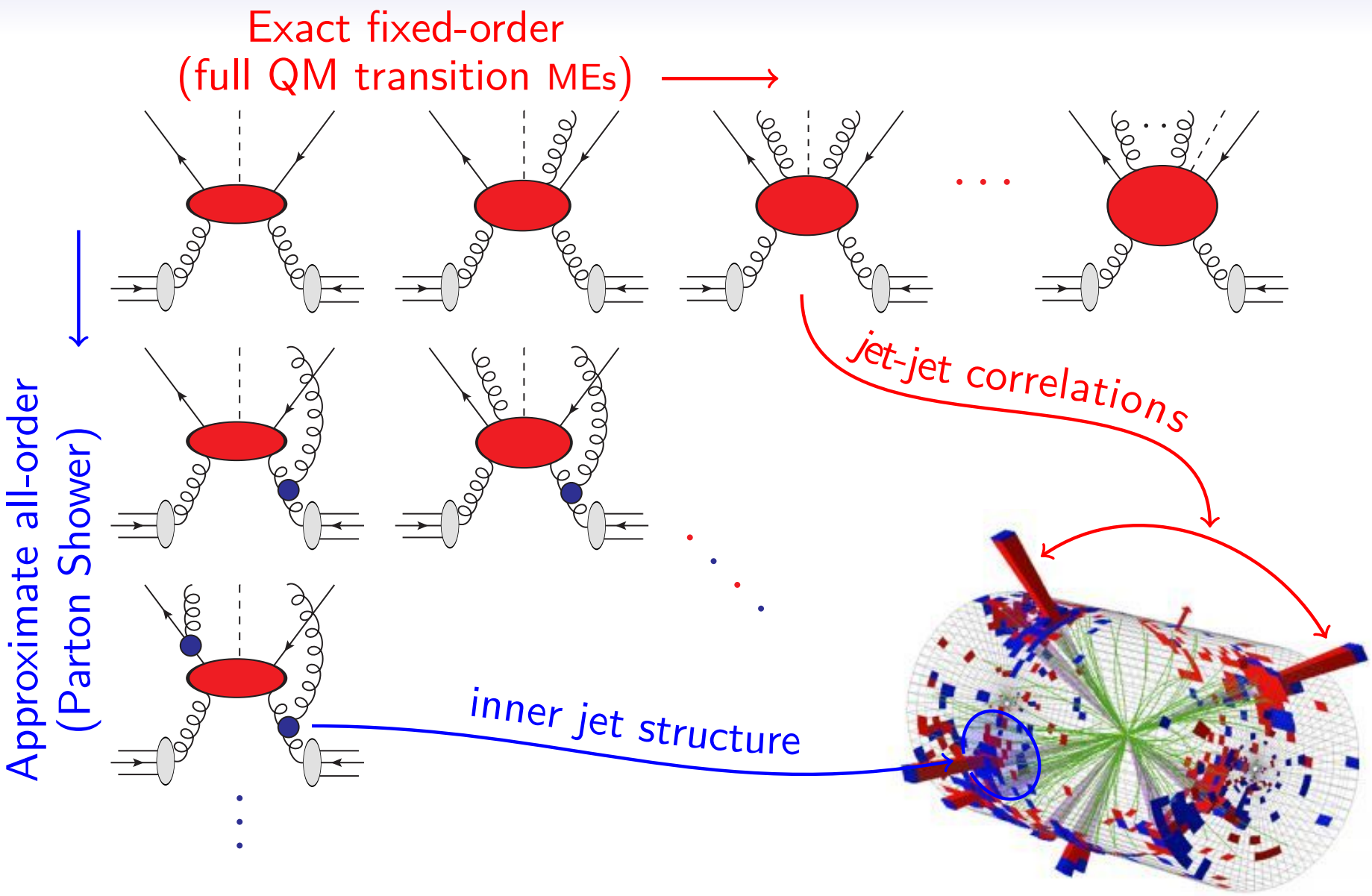


Solve DGLAP by **creating** all physical states in evolution
$\Rightarrow$ **Parton Shower**

$\Rightarrow$ Extracted all pert. dynamics from f !

$\Rightarrow$ jet of collinear partons


Exact fixed-order
(full QM transition MEs)
Approximate all-order
(Parton Shower)
jet-jet correlations
inner jet structure

Fixed-order calculations

Full quantum-mechanical calculation needed for jet correlations.
Dynamics captured by accurate scattering cross section $\hat{\sigma}$.
$\Rightarrow$ Calculate all Feynman diagrams at fixed coupling order.

NLO prediction of observable $\mathcal{O}$:

$$\langle \mathcal{O} \rangle^{\text{NLO}} = \int \mathrm{B}\ d\Phi\ \mathcal{O}(\Phi) + \int \mathrm{V}\ d\Phi\ \mathcal{O}(\Phi) + \int \mathrm{R}\ d\Phi_{+1}\ \mathcal{O}(\Phi_{+1})$$

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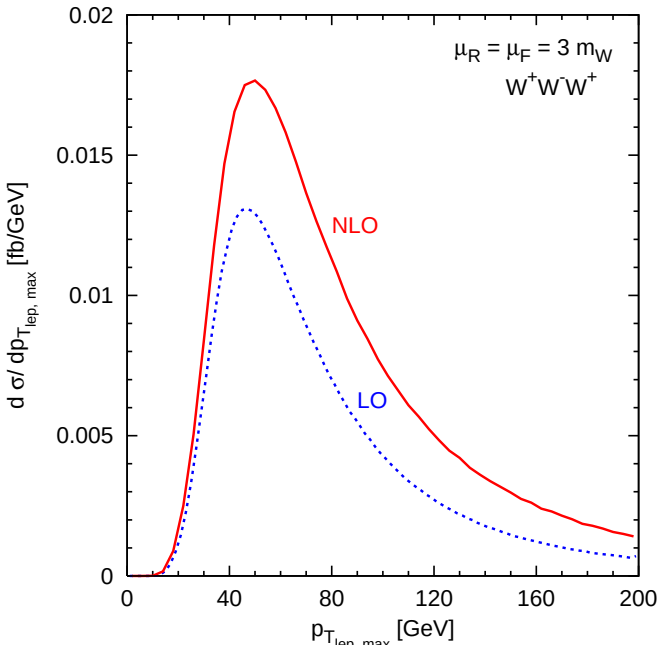
But integrals separately divergent, i.e. cannot produce plot numerically
Need to remove poles $\Rightarrow$ Subtract & add counterterm

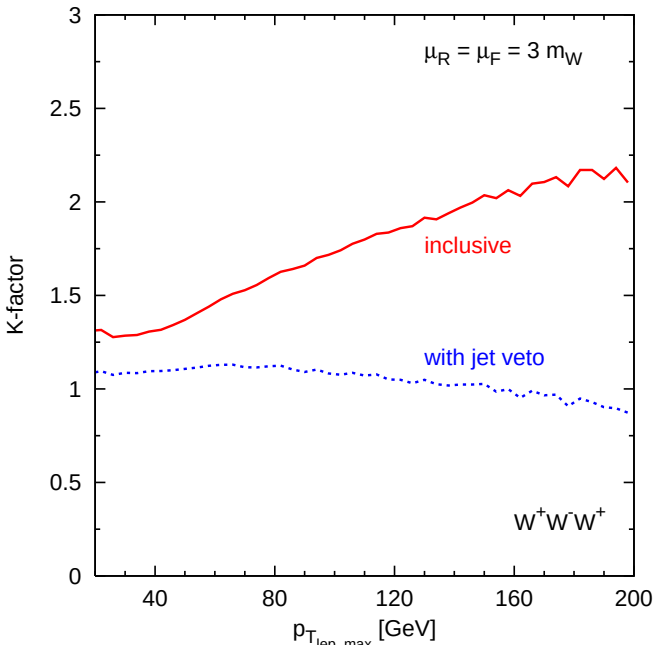
$$\langle \mathcal{O} \rangle^{\text{NLO}} = \int \left[\mathrm{B} + \mathrm{V} + \int \mathrm{S} \right] d\Phi\, \mathcal{O}(\Phi) + \int \left[\mathrm{R}\, \mathcal{O}(\Phi_{+1}) - \mathrm{S}\, \mathcal{O}(\Phi') \right] d\Phi_{+1}$$

$\Rightarrow$ Can predict "any" observable. Much tougher at higher orders.

NLO example

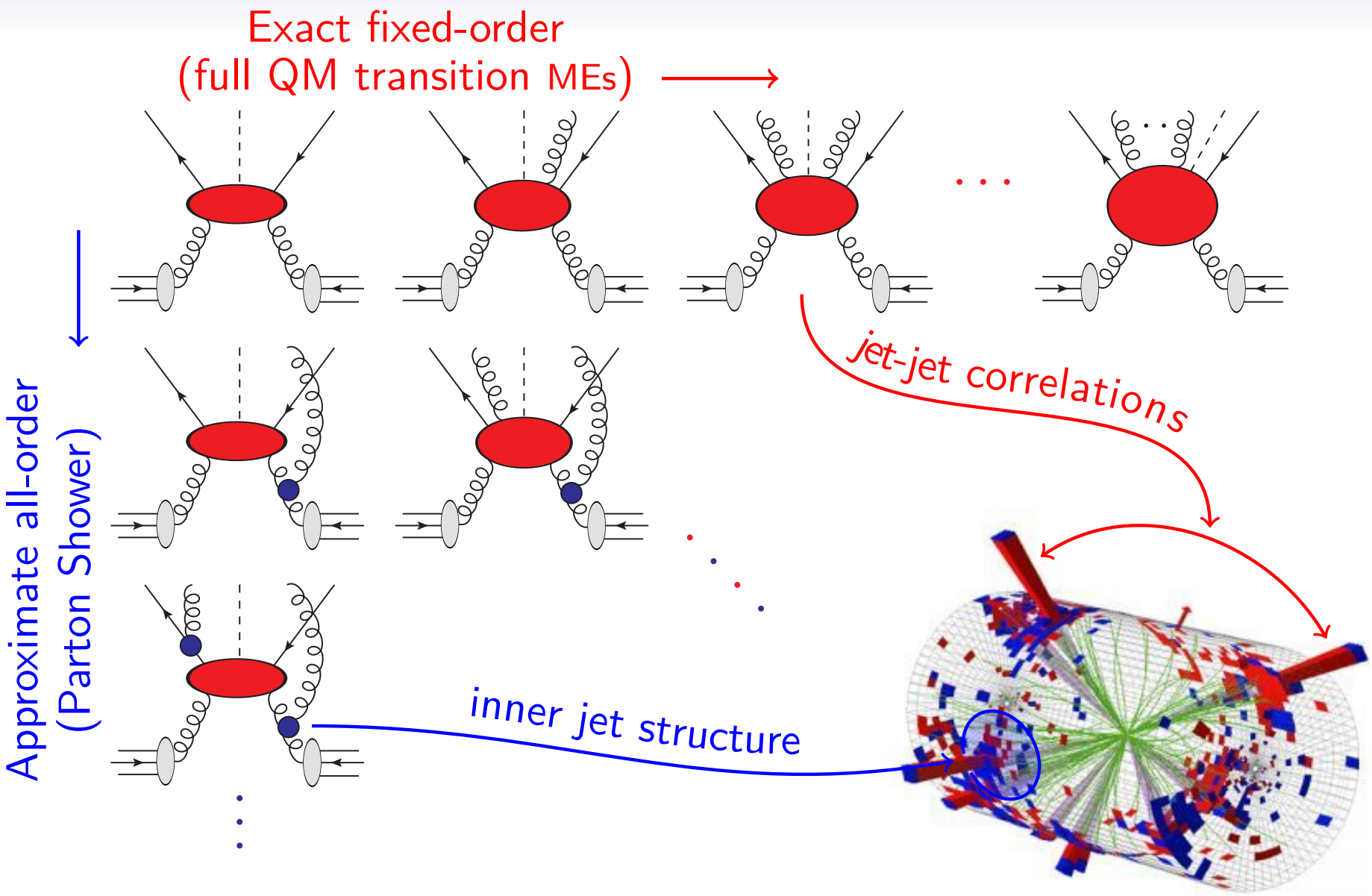
PRD 78 (2008) 094012
(Campanario, Hankele, Oleari, SP, Zeppenfeld)





NLO needed for better model of kinematics.

Most of the kinematic shift from well-separated (hard) real emission parton.
$\Rightarrow$ Complement to PS !


Exact fixed-order
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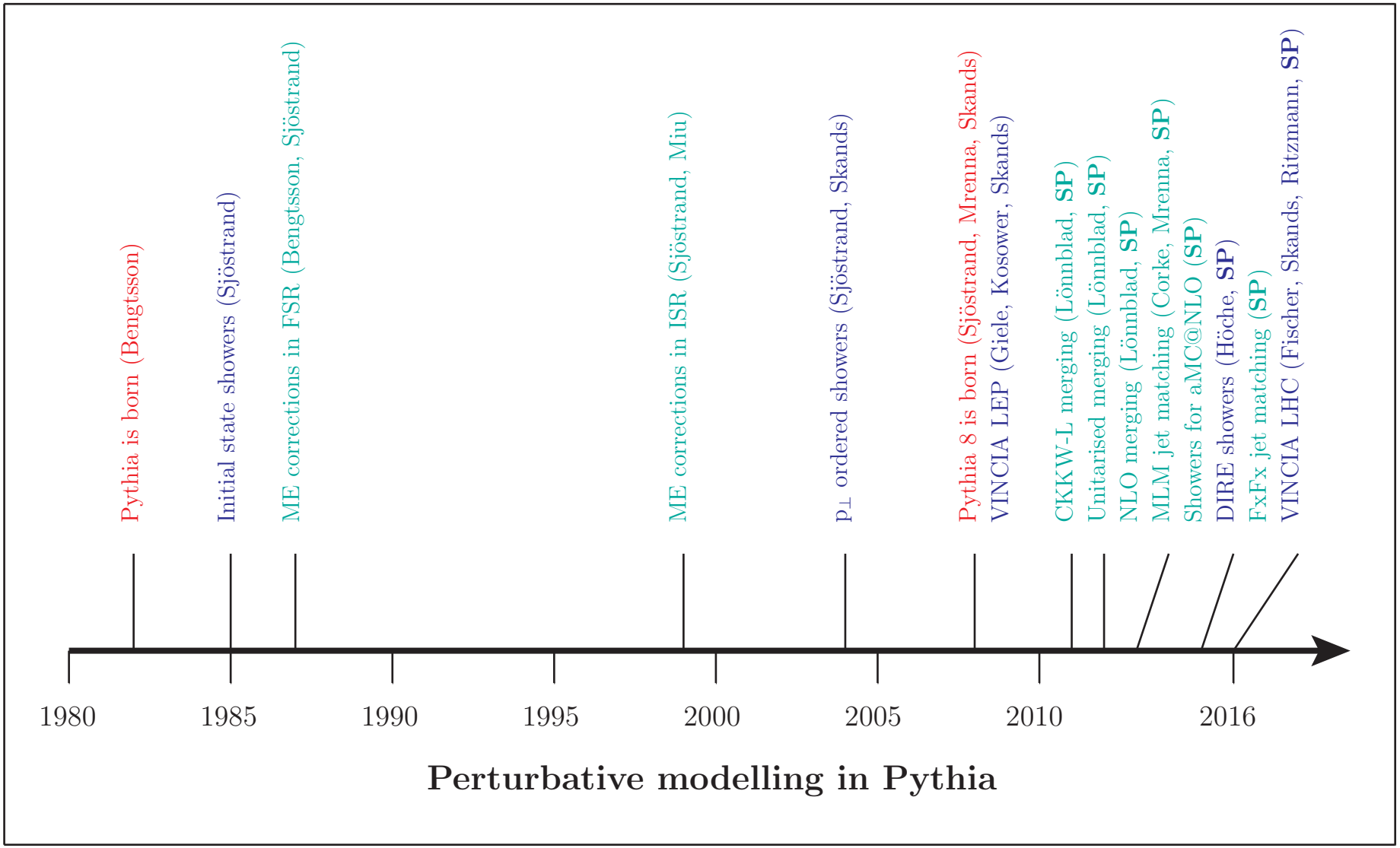
Pythia's perturbative timeline



Tools like MADGRAPH have less utility without tools like PYTHIA.

Merging fixed-order and PS: Subtract what you add!

JHEP 1302 (2013) 094, (Lönnblad, SP)

Remember: Probability conservation $\widehat{=}$ Subtract what you add:

$$\begin{aligned}
\textbf{PS}\,[\mathrm{B}_0] &= \underbrace{\mathrm{B}_0\Pi_0\mathcal{O}_0}_{\textbf{no emission}} + \underbrace{\int_1 \mathrm{B}_0 P\Pi_0 + \ldots}_{\textbf{at least 1 emission}} \\
&\equiv \mathrm{B}_0\mathcal{O}_0 - \int_1 \mathrm{B}_0 P\mathcal{O}_0\Pi_0 + \int_1 \mathrm{B}_0 P\Pi_0 + \ldots
\end{aligned}$$

$\Rightarrow$ Can then replace $\mathrm{B}_0 \cdot P(z_1) \cdot P(z_2) \cdots$ with complete result B_n if we always add and subtract:

$$\begin{aligned}
\textbf{ME+PS}\,[\mathrm{B}_0] &= \mathrm{B}_0\mathcal{O}_0 - \int_1 \mathrm{B}_1\mathcal{O}_0\Pi_0 + \int_1 \mathrm{B}_1\Pi_0 \\
&\quad - \int_2 \mathrm{B}_2\mathcal{O}_1\Pi_0\Pi_1 + \int_2 \mathrm{B}_2\Pi_0\Pi_1\,[\Pi_2\mathcal{O}_2 + \ldots]
\end{aligned}$$

$\Rightarrow$ Reproduces correct fixed-order accuracy, keeps PS accuracy.

Merging fixed-order and PS: Subtract what you add!

JHEP 1302 (2013) 094, (Lönnblad, SP)

Remember probability conservation $\widehat{=}$ Subtract what you add:

$$\mathbf{PS}\,[\mathrm{B}_0] \;=\; \mathrm{B}_0\Pi_0\mathcal{O}_0 + \int_1 \mathrm{B}_0 P\Pi_0 + \ldots$$

Take-home: Combine as many tree-level calculations as desired. Always subtract what we add.

Other LO merging schemes* are approximations of this *unitarised scheme*. All generators use a form of this by now (after some resistance).

Subtleties to solve and lots of technology needed to remain general and process-independent.

*(CKKW JHEP 0111 (2001) 063), (METS JHEP 0905 (2009) 053), (CKKW-L JHEP 1203 (2012) 019)

$$- \int_2 \mathrm{B}_2\Pi_0\Pi_1\mathcal{O}_1 + \int_2 \mathrm{B}_2\Pi_0\Pi_1\left[\Pi_2\mathcal{O}_2 + \ldots\right]$$

$\Rightarrow$ Reproduces correct fixed-order accuracy, keeps PS accuracy.

Do you need ME+PS for BSM signals?

JHEP 1203 (2012) 019 (Lönnblad, SP)
PRD87 (2013) 3, 035006 (Dreiner, Krämer, Tattersall)

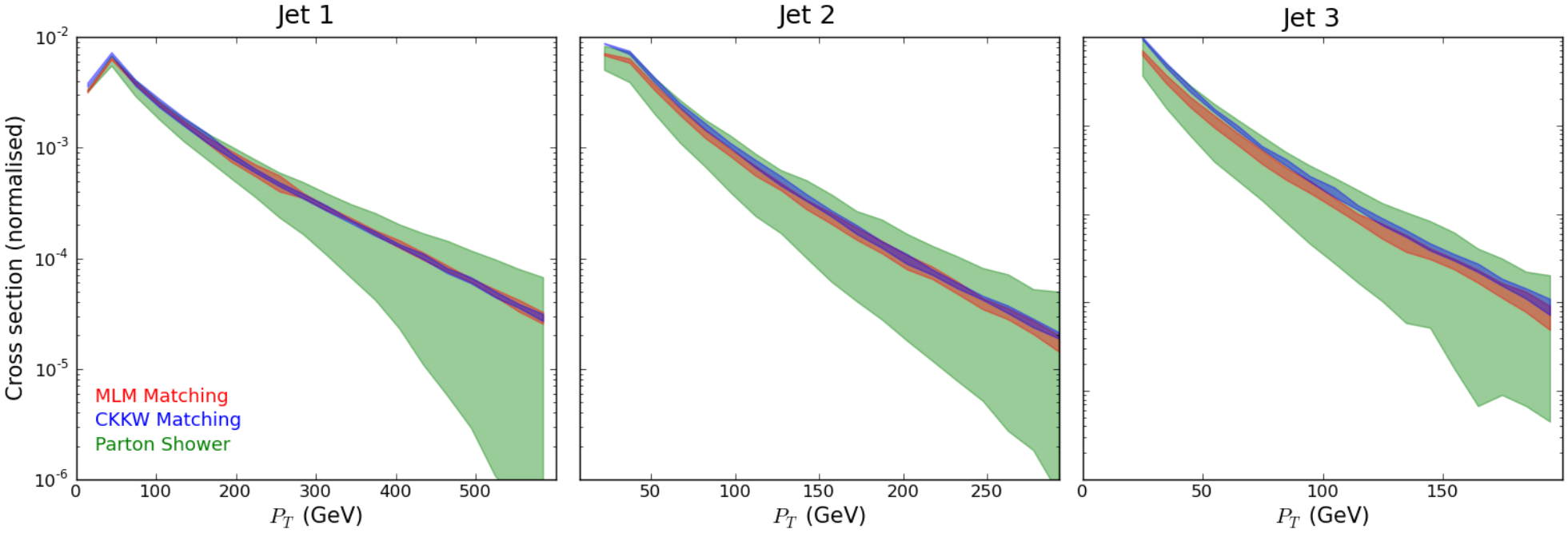


Figure: Jet $p_\perp$s for squarks+jets. PS bands are obtained by varying between "wimpy" and "power shower", merged bands by varying the merging scale from $50 - 200$ GeV. (NB: CKKW-L: Until unitarisation, most sophisticated LO merging scheme.)

$\Longrightarrow$ Improved QCD pins down the transverse momenta.

...and how good is your exclusion?

JHEP 1203 (2012) 019 (Lönnblad, SP)
PRD87 (2013) 3, 035006 (Dreiner, Krämer, Tattersall)

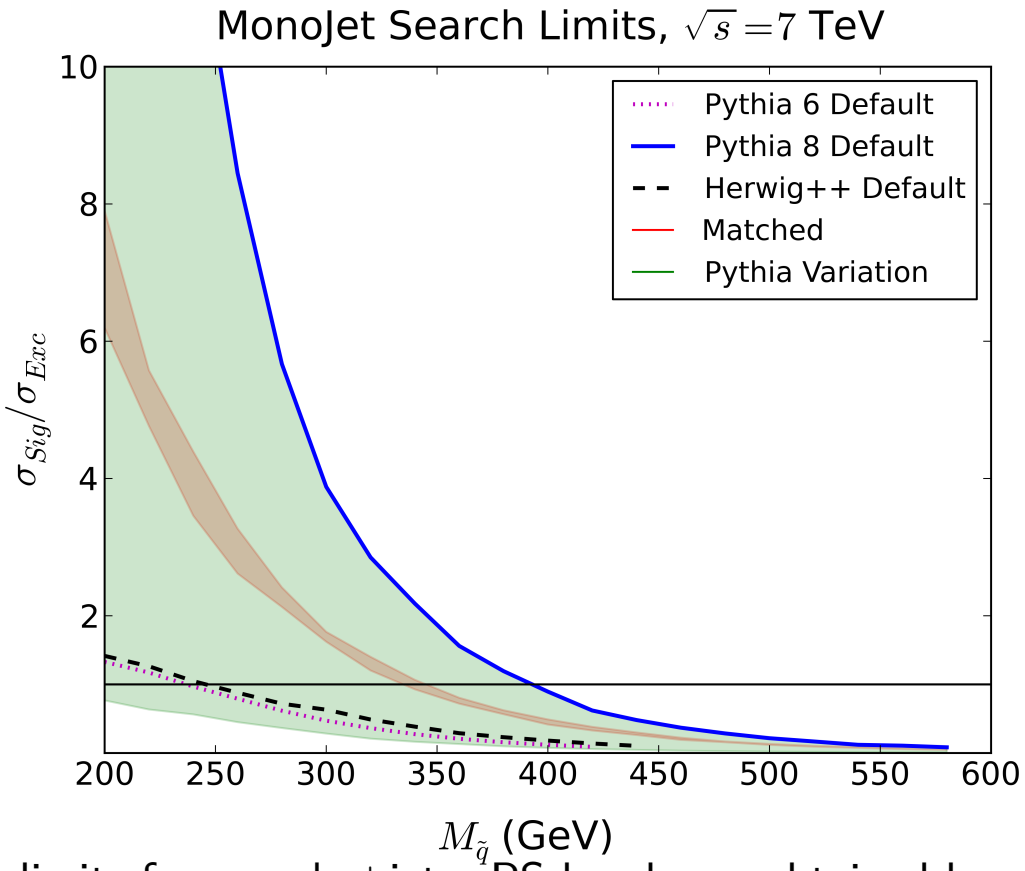
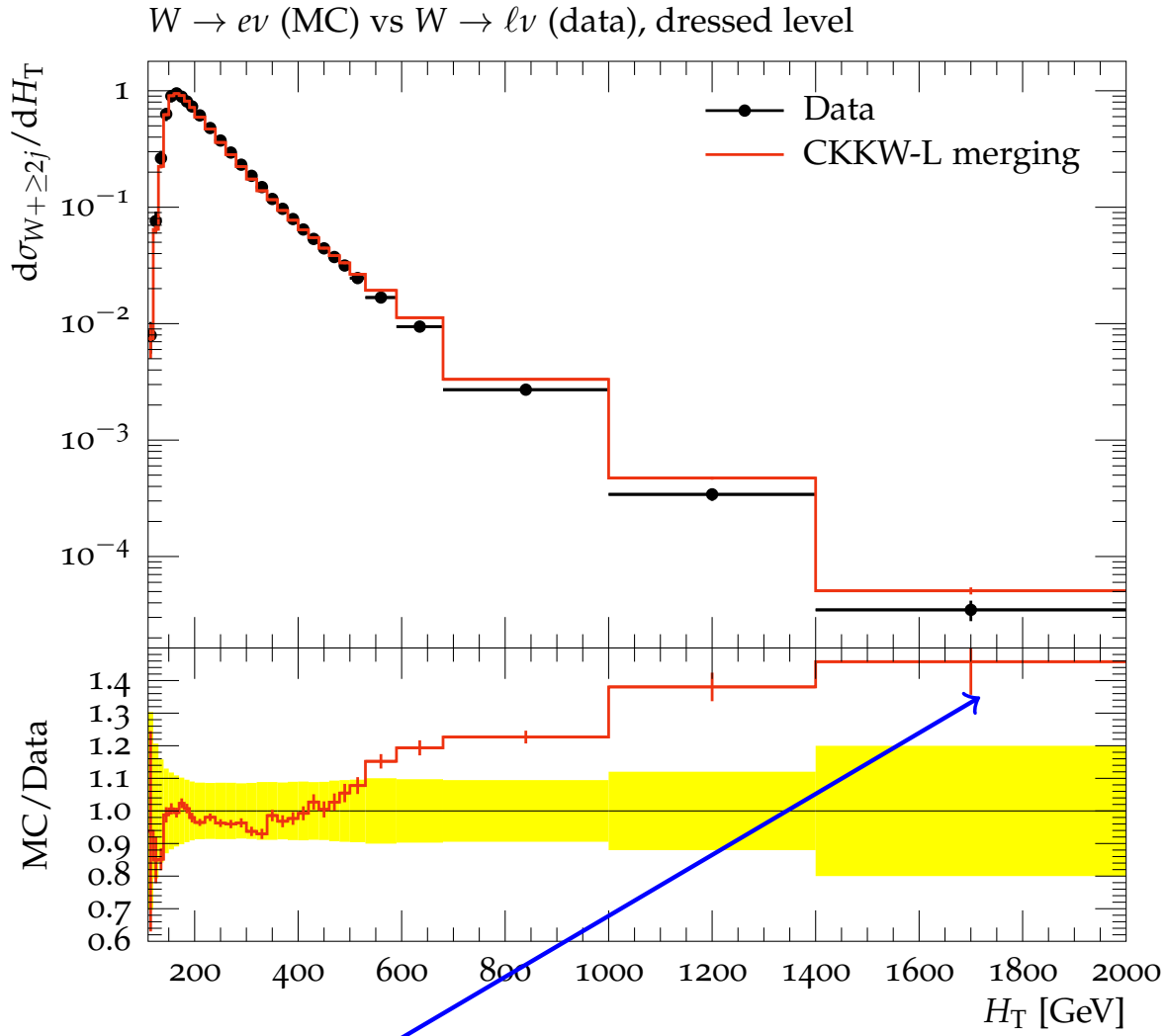


Figure: Exclusion limits for squarks+jets. PS bands are obtained by varying between "wimpy" and "power shower", merged bands by varying the merging scale from $50 - 200$ GeV.
(NB: CKKW-L: Until unitarisation, most sophisticated LO merging scheme.)

⇒ Improved QCD pins down jet momenta, reducing MC uncertainties.

Too much of a good thing?

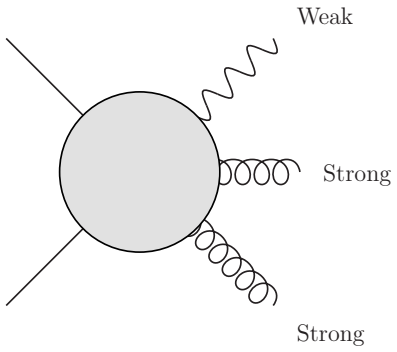
EPJC 76 (2016) 1, 39 (Christiansen, SP)



What happened?!

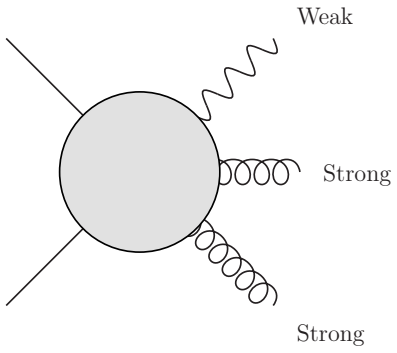
Advanced background simulation fails in SUSY search region!

Too much of QCD

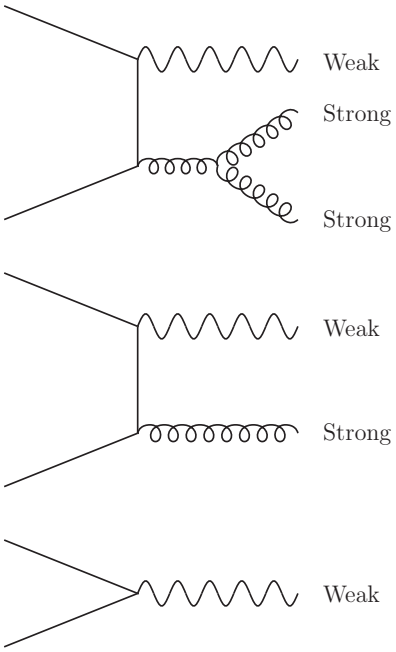


The problem: If it looks like QCD, is it a QCD correction?

Too much of QCD

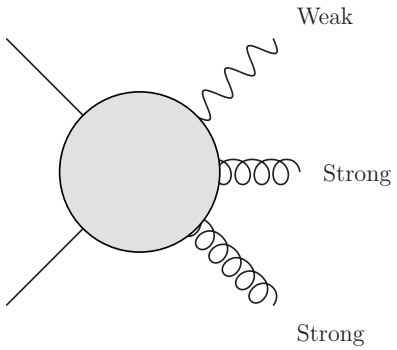


Drell-Yan + QCD correction

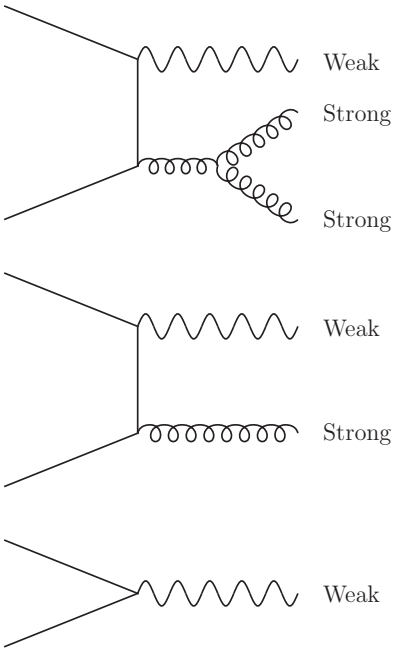


The problem: If it looks like QCD, is it a QCD correction?
This is!
$\Rightarrow$ All-order structure governed by QCD.

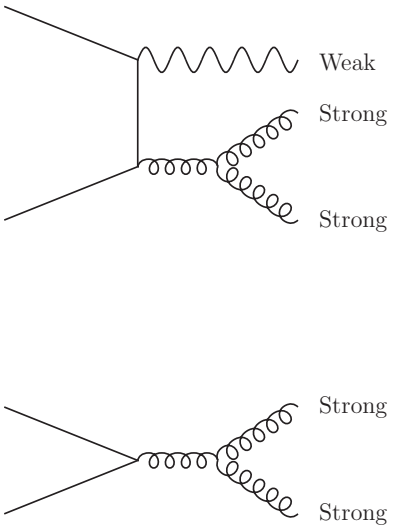
Too much of QCD



Drell-Yan + QCD correction

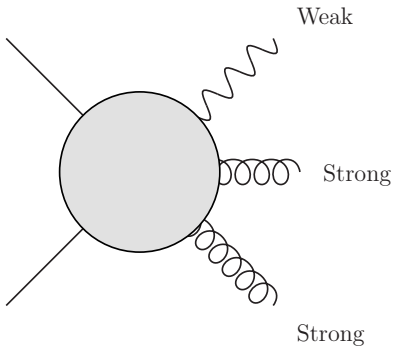


Dijet + EW correction



The problem: If it looks like QCD, is it a QCD correction?
This is **not!**
Scales very different.

Too much of QCD

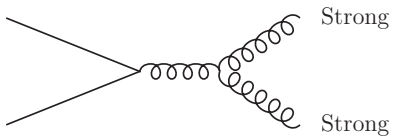


Drell-Yan + QCD correction

Dijet + EW correction

Higher-order terms (*i.e. scales in running coupling, resummed Sudakov logarithms*) are very different in either case.

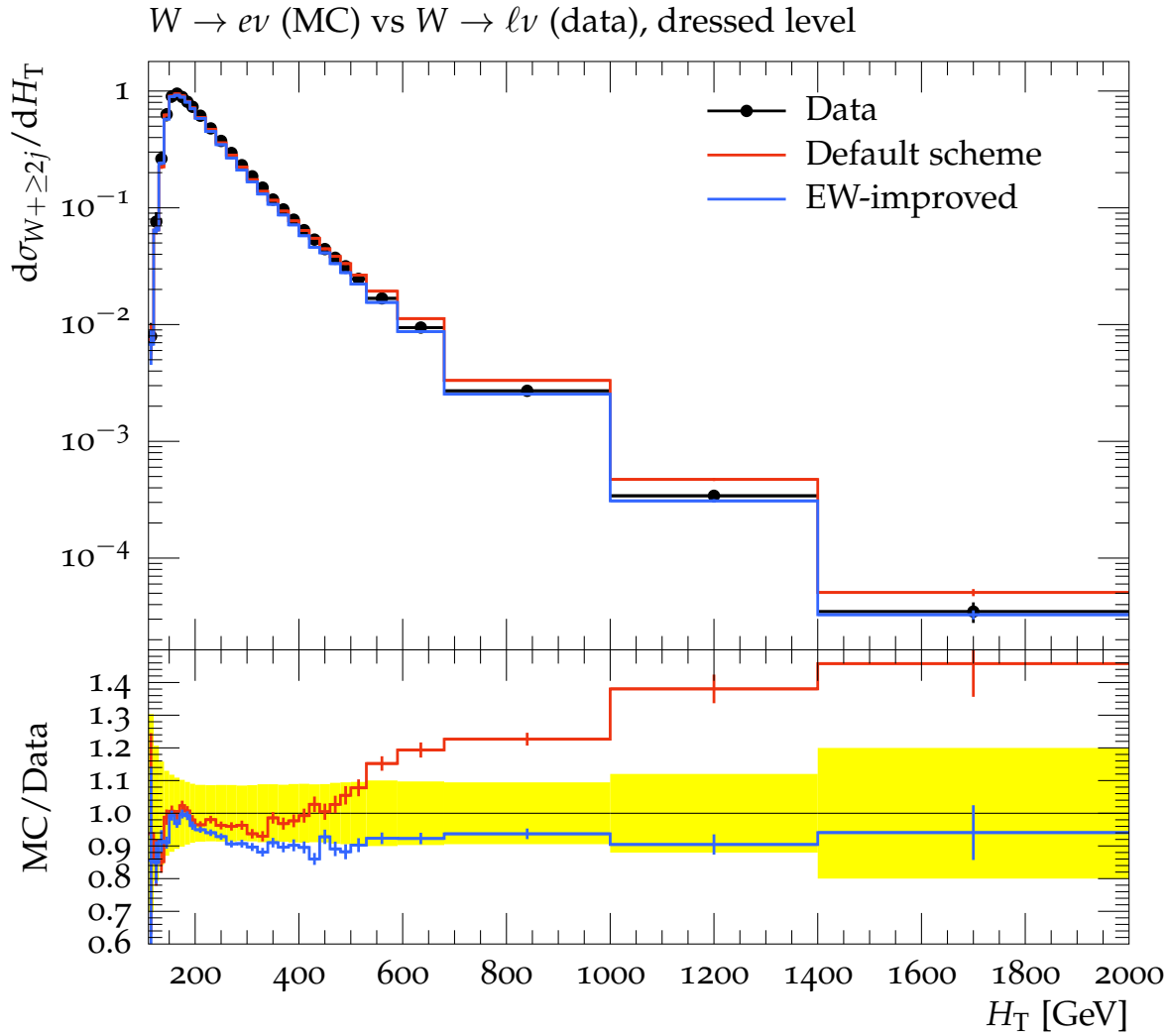
Large impact if all-order terms not handled with care:
QCD resummation *and* electroweak resummation needed for reliable result.



The problem: If it looks like QCD, is it a QCD correction?
This is **not!**
Scales very different.

Electroweak merging results

EPJC 76 (2016) 1, 39 (Christiansen, SP)



Important for 100 TeV !

Merging needs to go beyond QCD corrections:

Need QCD resummation + EW resummation ($\ln \frac{p_{\perp V}}{M_V}$) + multi-jet MEs + multi-V MEs

So where did the NLO go?!?
We quietly dropped the "accurate" – used only real emissions.
Need to reinstate the accuracy.

NLO merging

NLO multi-jet merging from LO scheme **X**:

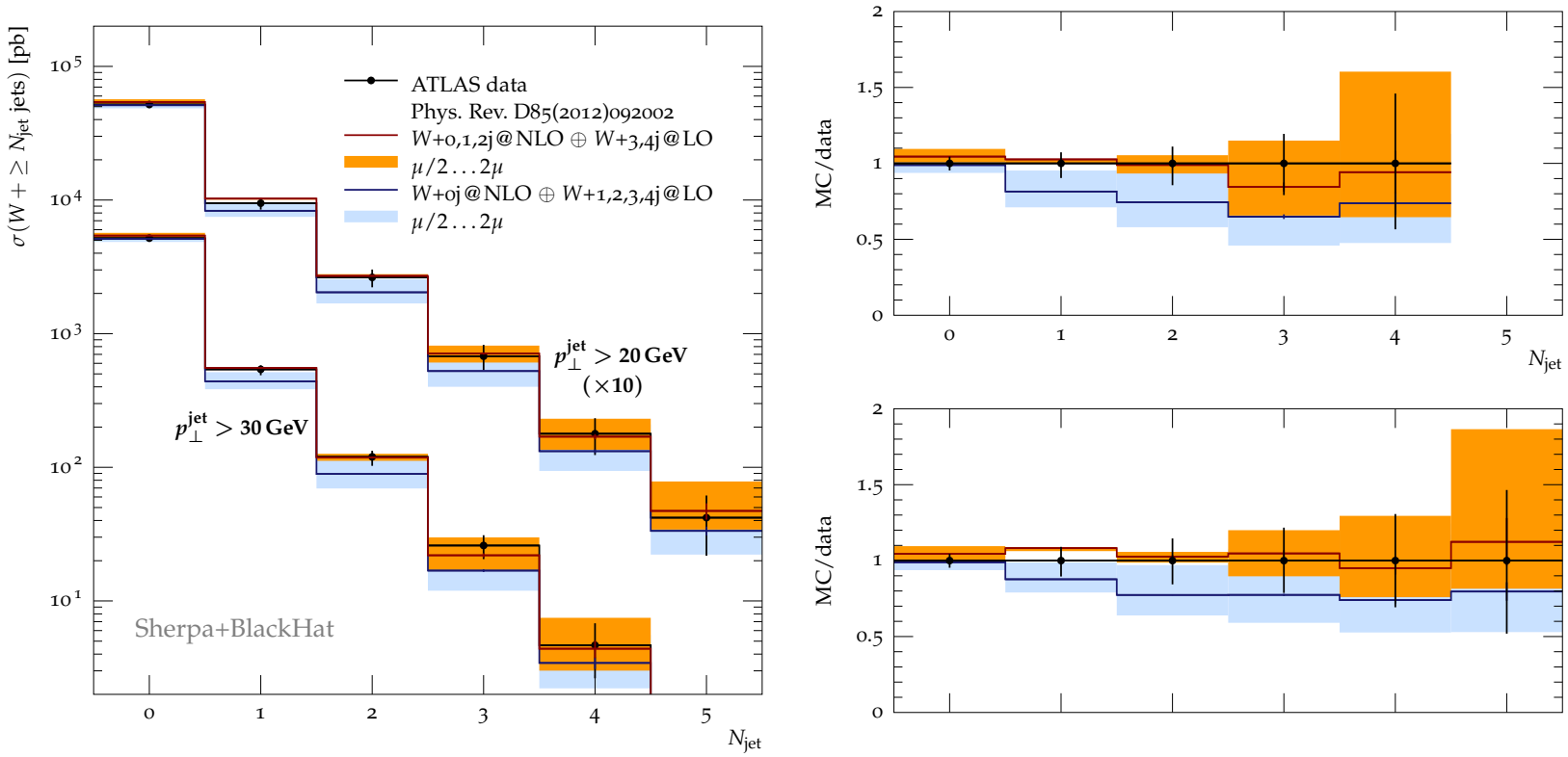
- Subtract approximate $\mathcal{O}(\alpha_s)$-terms produced in **X**, add multiple NLO calculations to get correct $\mathcal{O}(\alpha_s)$.
- Ensure real-emission terms do not overlap.
- Subtract what you add to preserve the inclusive cross section.

The direct NLO extension of the "unitarized scheme" is called UNLOPS. Other NLO merging schemes* **X**@NLO are approximation thereof.

*(MEPS@NLO JHEP 1304 (2013) 027, (FxFx JHEP 1212 (2012) 061)

Uncertainty reduction

JHEP 1304 (2013) 027
(Höche, Krauss, Schönherr, Siegert)



NLO merging reduces the uncertainties

$\Rightarrow$ More accurate dynamics.

More accurate BSM background description.

NLO merged results for squarks + jets

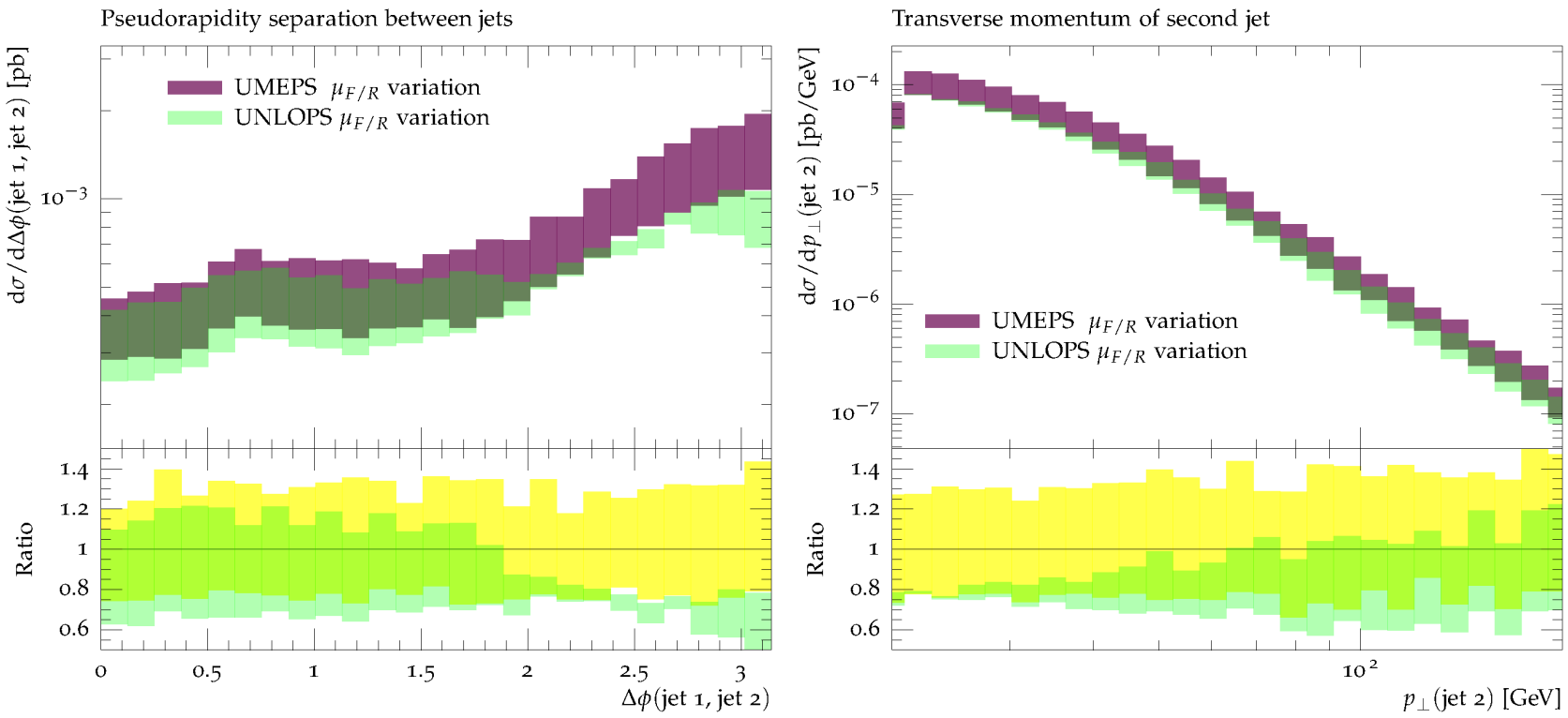


Figure: $\Delta\phi_{12}$ and $p_{\perp 2}$ for u-squark pair production after merging (squarks+0)@NLO, (squarks+1)@LO and (squarks+2)@LO.

$\Rightarrow$ Uncertainty goes down, as expected – but effects not large enough to be exciting. Good news for pheno!

NB: On-shell complicates problem.

Breaching the precision frontier: Matching @ NNLO

For important processes, precision is key!
That includes luminosity monitors (Drell-Yan), studies of the Higgs...
Precision reduces uncertainties.

Observation: If an NLO merged calculation has stable inclusive cross section, it is straight forward to upgrade this cross section to NNLO.
$\Longrightarrow$ Fulfilled by the UNLOPS scheme

Rough idea:

1. Assume NNLO in a slicing method
2. Perform UNLOPS merging on configurations above the slicing cut.
3. Ensure that parton shower does not introduce any terms at $\mathcal{O}(\alpha_s^2)$

Deriving the UN^{2}LOPS matching

PRD 91 (2015) 7, 074015 (Höche, Li, SP)

$$\mathcal{O}^{(\mathrm{UN^2LOPS})} = \int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_T,\mathrm{cut}}(\Phi_0)\, O(\Phi_0)$$

$$+ \int_{q_T,\mathrm{cut}} d\Phi_1 \qquad \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O)$$

$$+ \int_{q_T,\mathrm{cut}} d\Phi_1 \qquad \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O)$$

$$+ \int_{q_T,\mathrm{cut}} d\Phi_2 \qquad \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, \mathcal{F}_2(t_2, O)$$

$$+ \int_{q_T,\mathrm{cut}} d\Phi_2\; \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2, O)$$

Start with NNLO cross section.
$\mathcal{F}_i$ indicate that the PS will start from $+i$-parton state.

Deriving the UN^{2}LOPS matching

PRD 91 (2015) 7, 074015 (Höche, Li, SP)

$$\mathcal{O}^{(\mathrm{UN^2LOPS})} = \int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_T,\mathrm{cut}}(\Phi_0)\, O(\Phi_0)$$

$$+ \int_{q_T,\mathrm{cut}} d\Phi_1 \qquad \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O)$$

$$+ \int_{q_T,\mathrm{cut}} d\Phi_1 \left[1 - \Pi_0(t_1, \mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, O(\Phi_0) + \int_{q_T,\mathrm{cut}} d\Phi_1 \Pi_0(t_1, \mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O)$$

$$+ \int_{q_T,\mathrm{cut}} d\Phi_2 \left[1 - \Pi_0(t_1, \mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, O(\Phi_0) + \int_{q_T,\mathrm{cut}} d\Phi_2\, \Pi_0(t_1, \mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, \mathcal{F}_2(t_2, O)$$

$$+ \int_{q_T,\mathrm{cut}} d\Phi_2\, \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2, O)$$

Calculate and attach resummed factors to "true" NLO terms.
And keep the correct cross section by "subtract what you add".

Deriving the UN^{2}LOPS matching

PRD 91 (2015) 7, 074015 (Höche, Li, SP)

$$
\begin{aligned}
\mathcal{O}^{(\mathrm{UN^2LOPS})} = & \int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_T,\mathrm{cut}}(\Phi_0)\, O(\Phi_0) \\
& + \int_{q_T,\mathrm{cut}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1(\Phi_1)\, O(\Phi_0) \\
& + \int_{q_T,\mathrm{cut}} d\Phi_1\, \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O) \\
& + \int_{q_T,\mathrm{cut}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, O(\Phi_0) + \int_{q_T,\mathrm{cut}} d\Phi_1 \Pi_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O) \\
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& + \int_{q_T,\mathrm{cut}} d\Phi_2\, \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2, O)
\end{aligned}
$$

Calculate and attach resummed factors to tree-level terms.
And ensure not to introduce bad $\mathcal{O}(\alpha_s^2)$ terms.
And keep the correct cross section by "subtract what you add".

Deriving the UN^{2}LOPS matching

PRD 91 (2015) 7, 074015 (Höche, Li, SP)

$$
\begin{aligned}
\mathcal{O}^{(\mathrm{UN^2LOPS})} = & \int d\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{q_T,\mathrm{cut}}(\Phi_0)\, O(\Phi_0) \\
& + \int_{q_T,\mathrm{cut}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1(\Phi_1)\, O(\Phi_0) \\
& + \int_{q_T,\mathrm{cut}} d\Phi_1\, \Pi_0(t_1,\mu_Q^2)\left(w_1(\Phi_1) + w_1^{(1)}(\Phi_1) + \Pi_0^{(1)}(t_1,\mu_Q^2)\right) \mathrm{B}_1(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O) \\
& + \int_{q_T,\mathrm{cut}} d\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, O(\Phi_0) + \int_{q_T,\mathrm{cut}} d\Phi_1 \Pi_0(t_1,\mu_Q^2)\, \tilde{\mathrm{B}}_1^{\mathrm{R}}(\Phi_1)\, \bar{\mathcal{F}}_1(t_1, O) \\
& + \int_{q_T,\mathrm{cut}} d\Phi_2 \left[1 - \Pi_0(t_1,\mu_Q^2)\right] \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, O(\Phi_0) + \int_{q_T,\mathrm{cut}} d\Phi_2\, \Pi_0(t_1,\mu_Q^2)\, \mathrm{H}_1^{\mathrm{R}}(\Phi_2)\, \mathcal{F}_2(t_2, O) \\
& + \int_{q_T,\mathrm{cut}} d\Phi_2\, \mathrm{H}_1^{\mathrm{E}}(\Phi_2)\, \mathcal{F}_2(t_2, O)
\end{aligned}
$$

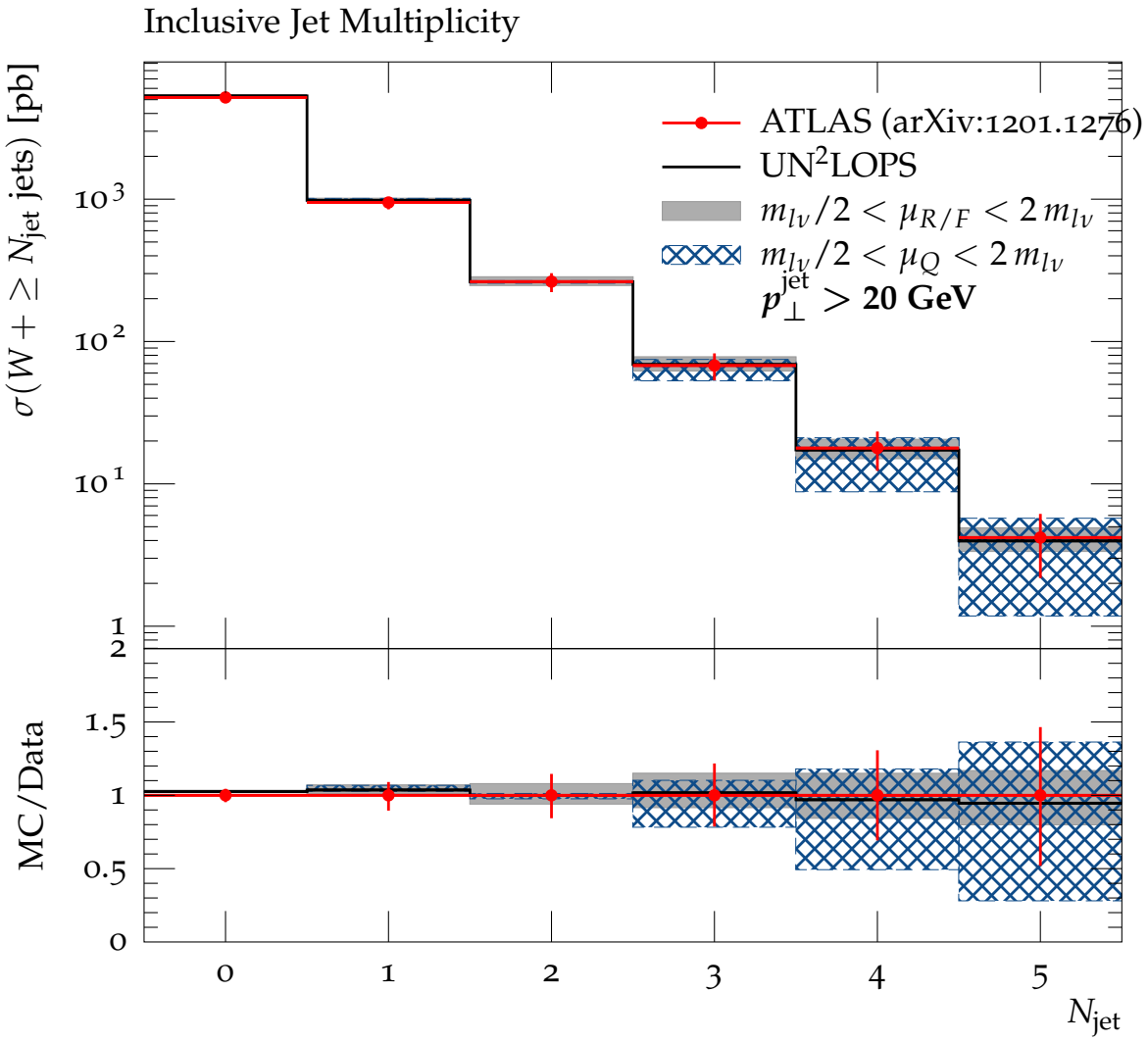
NNLO accuracy preserved by construction.

PS accuracy preserved since all-order factors generated by PS.

$\Rightarrow$ NNLO+PS matching.

UN^{2}LOPS results (NNLO+PS matched)

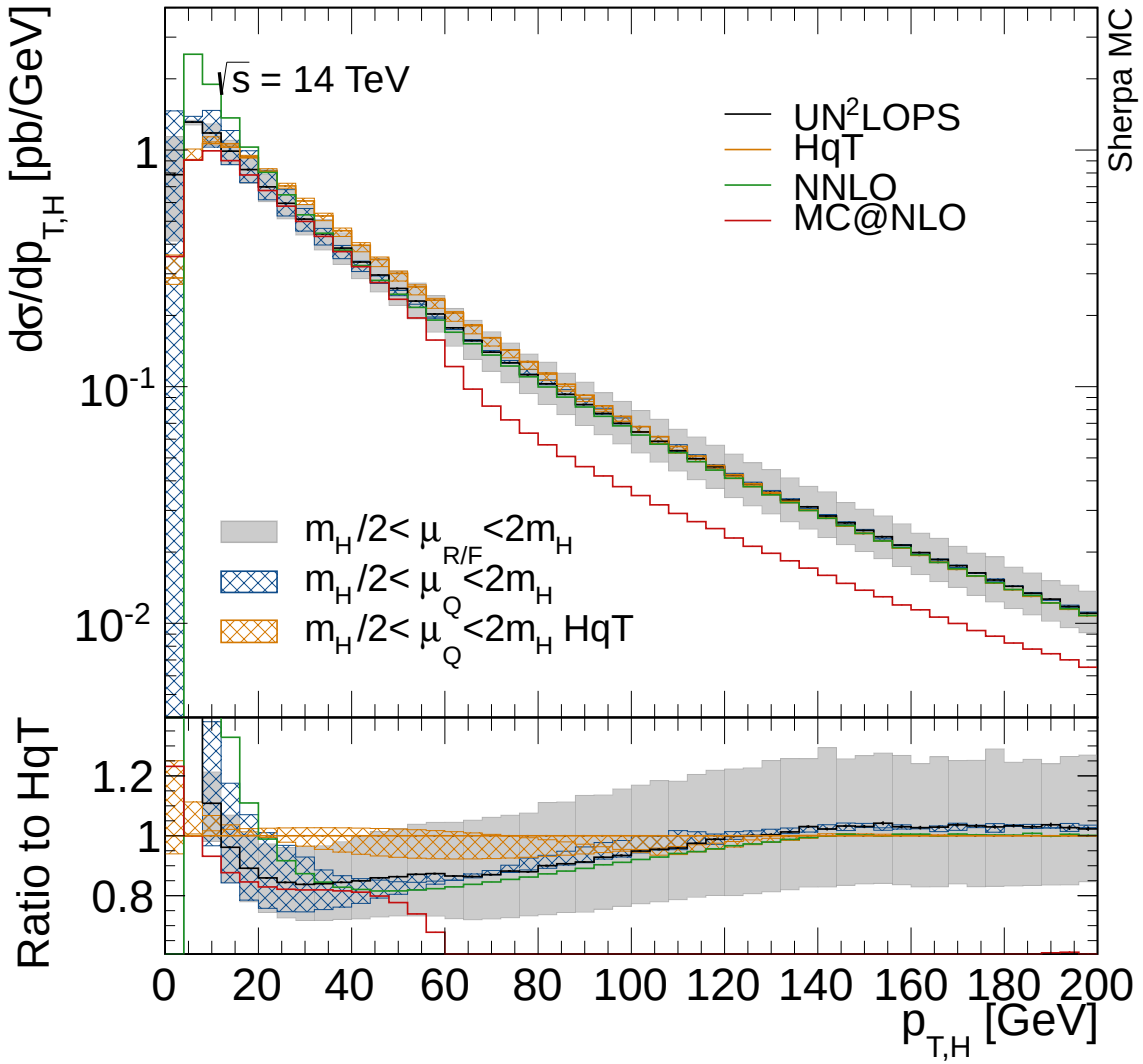
PRD 91 (2015) 7, 074015 (Höche, Li, SP)



n_{jets} in association with a Z-boson. UN^{2}LOPS has (very) small uncertainty in zero/one-jet rate. Shower uncertainty larger for higher multiplicities.

UN^{2}LOPS (Higgs production)

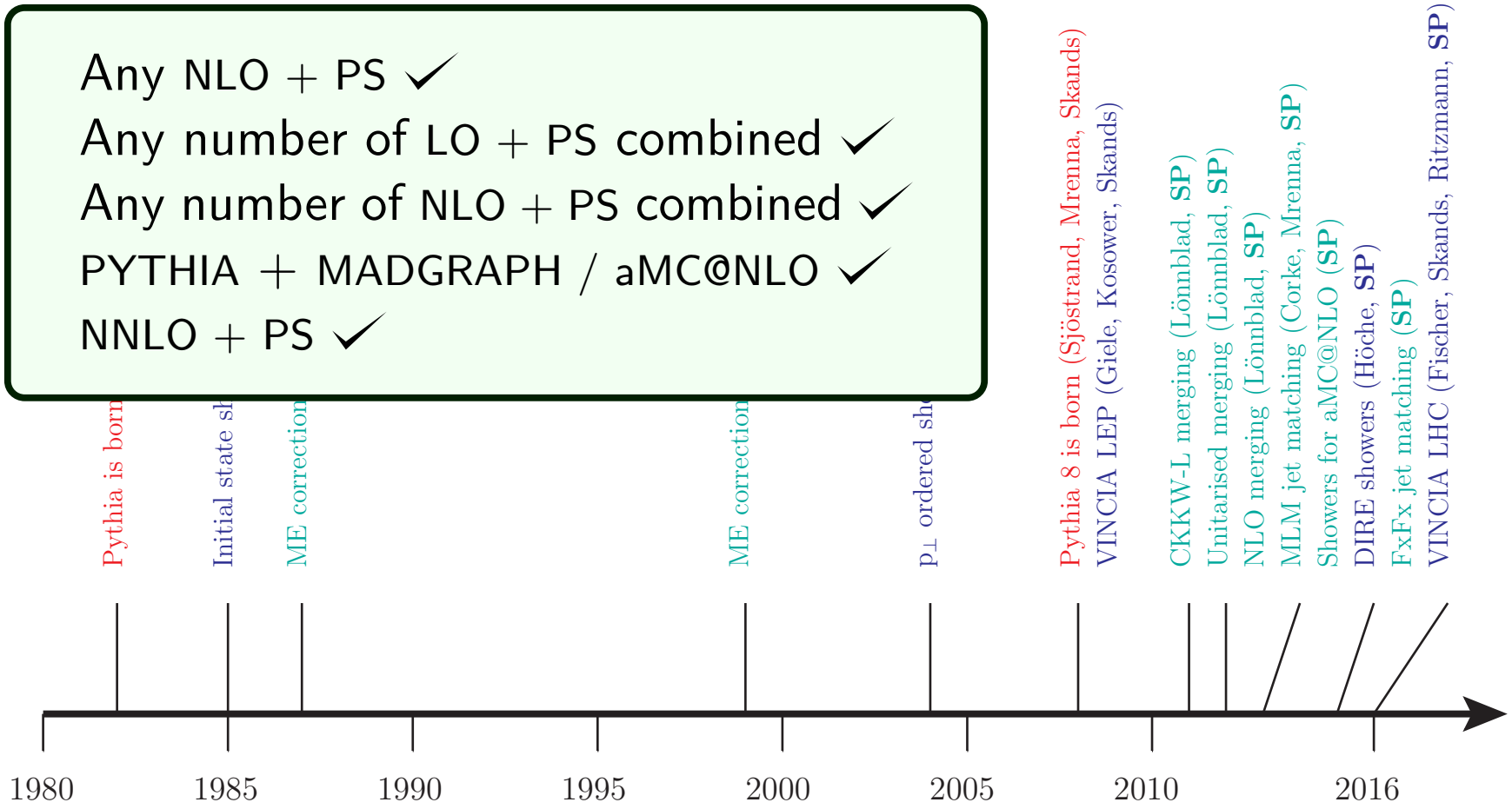
PRD 90 (2014) 5, 054011 (Höche, Li, SP)



$p_\perp$ of the Higgs-boson in UN^{2}LOPS, compared to *dedicated* calculation. NLO matching bad, UN^{2}LOPS matches HqT within (large) uncertainties.

The story so far

Any NLO + PS ✓
Any number of LO + PS combined ✓
Any number of NLO + PS combined ✓
PYTHIA + MADGRAPH / aMC@NLO ✓
NNLO + PS ✓

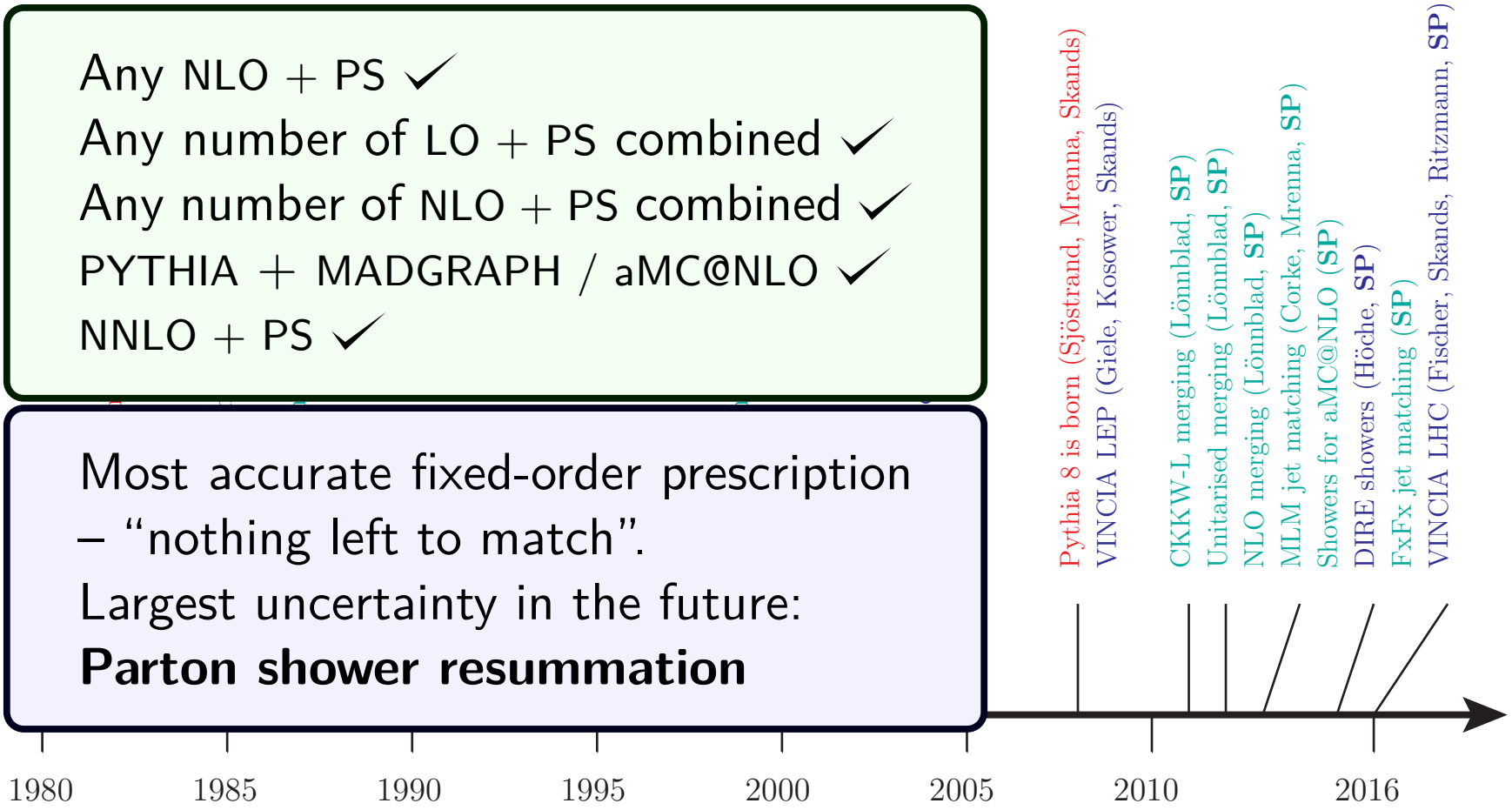


Perturbative modelling in Pythia

The story so far

Any NLO + PS ✓
Any number of LO + PS combined ✓
Any number of NLO + PS combined ✓
PYTHIA + MADGRAPH / aMC@NLO ✓
NNLO + PS ✓

Most accurate fixed-order prescription – "nothing left to match".
Largest uncertainty in the future:
Parton shower resummation



Perturbative modelling in Pythia

The need for new parton showers

Parton shower $\widehat{=}$ Exclusive implementation of evolution equations.
Resums dominant perturbative terms to all orders.

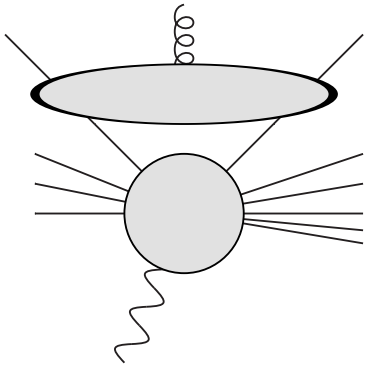
My goal:
Shower at least as accurate description as dedicated calculations.
+ give precise all-order QCD predictions for everything else!

This is the only sustainable strategy for the future.

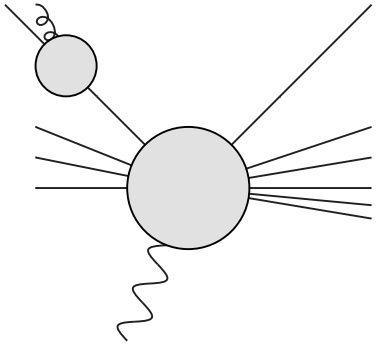
No older PS is sufficiently well-defined to make this possible.

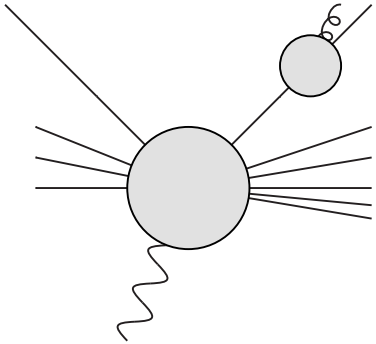
$\Rightarrow$ **Start over. Understand dynamics in soft and collinear limits and stay simple and extendable!**

Soft and collinear limits



Long-wavelength gluons see only color density
$\Rightarrow$ Needs correlated emissions from color dipoles or color multipoles.





Collinear gluons see "independent" jets
$\Rightarrow$ Needs factorized (DGLAP) evolution.

DIRE showers

EPJC 75 (2015) 9, 461 (Höche, SP)

Construction principles of a new shower:

Soft limit and collinear limit disentangled

Helps to find improvements.

Dominant two-particle correlation in soft limit reproduced

Choose two-particle symmetric resolution (=ordering) variable

Simple phase space boundaries

Allows comparison to dedicated calc. as phase space integration manageable

DIPOLERESUMMATION with a parton shower.
Combines "traditional" *parton* showers and *dipole* showers.

DIRE showers

EPJC 75 (2015) 9, 461 (Höche, SP)

Construction principles of a new shower:

Soft limit and collinear limit disentangled

Helps to find improvements.

Dominant two-particle correlation in soft limit reproduced

Choose two-particle symmetric resolution (=ordering) variable

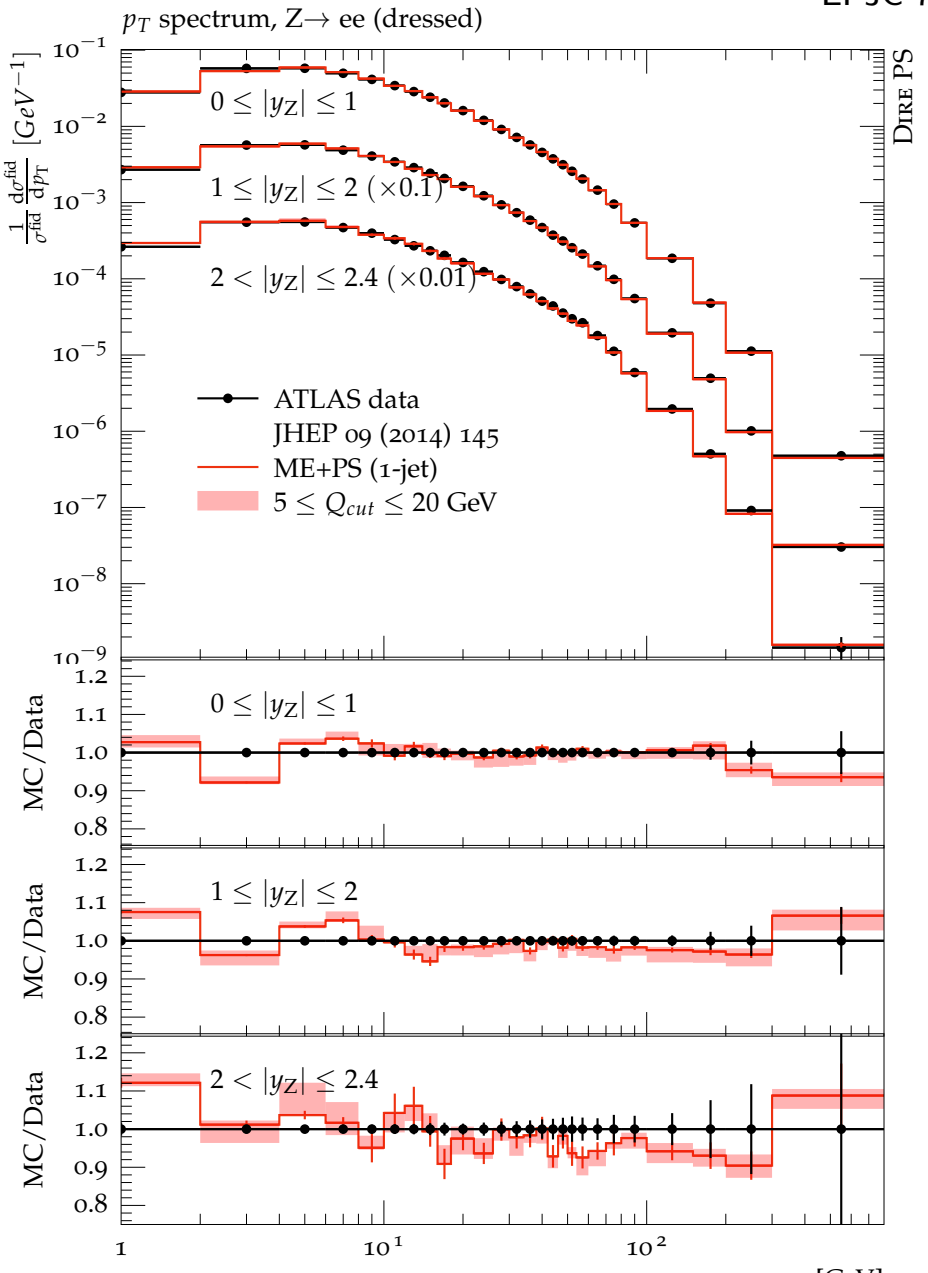
Implemented simultaneously and independently in PYTHIA and SHERPA.
First time a shower has been cross-validated!

Allows comparison to dedicated calc. as phase space integration manageable

DIPOLERESUMMATION with a parton shower.
Combines "traditional" *parton* showers and *dipole* showers.

DIRE predictions

EPJC 75 (2015) 9, 461 (Höche, SP)



Pushing the all-order accuracy of showers

[in preparation]

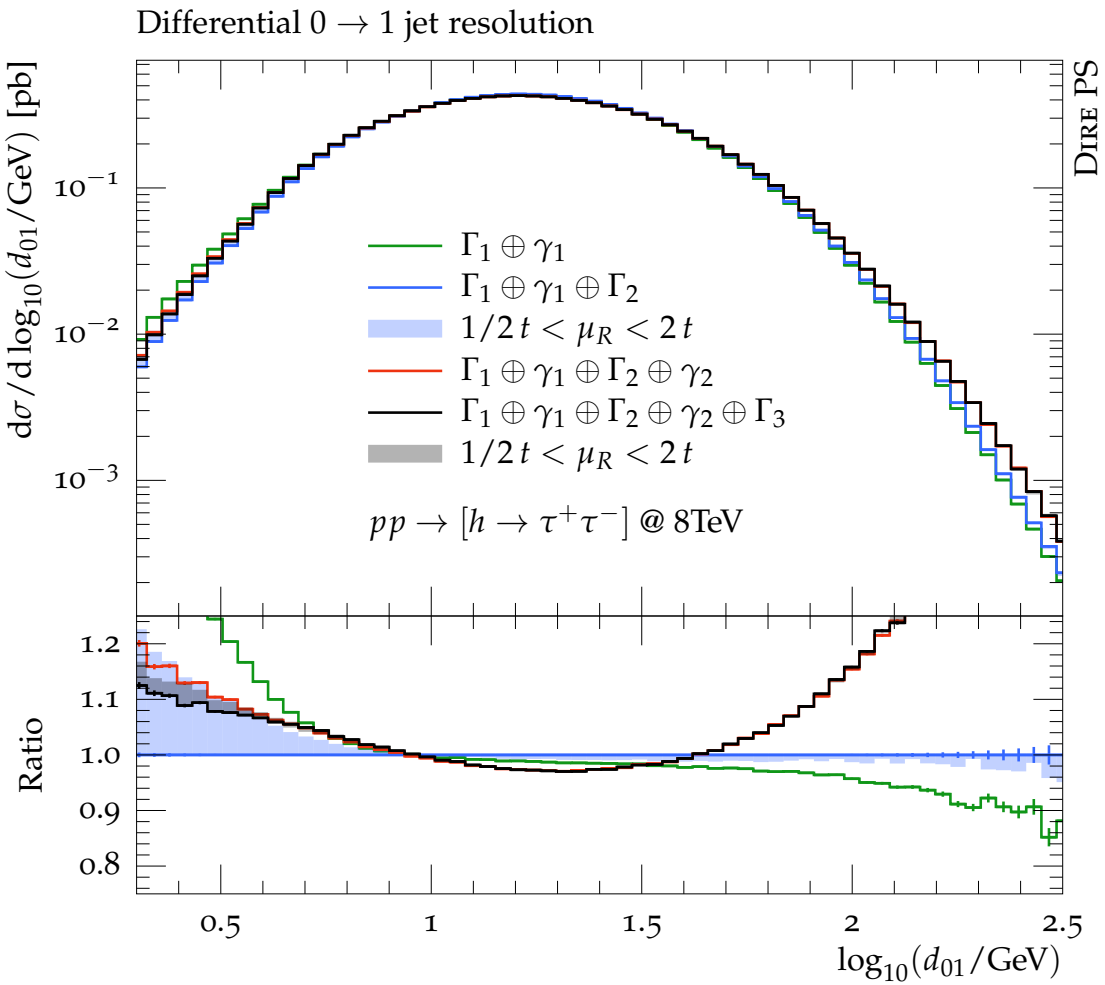
DIRE constructed to have manageable analytic structure.
$\Rightarrow$ Compare against dedicated analytic calculations (if available).
$\Rightarrow$ Find subleading dynamics & generate fully differentially in DIRE.

First steps:

- Included $1 \to 3$ splittings ("pure NNLO" only so far)
- Included up to three-loop soft terms (cusp anomalous dimension).
- Included NNLO AP kernels.

DIRE+ preliminary results

[in preparation]



⇒ Higher accuracy means all-order uncertainty decreases.

VINCIA for hadron colliders

[in preparation (Skands, Fischer, Ritzmann, SP)]

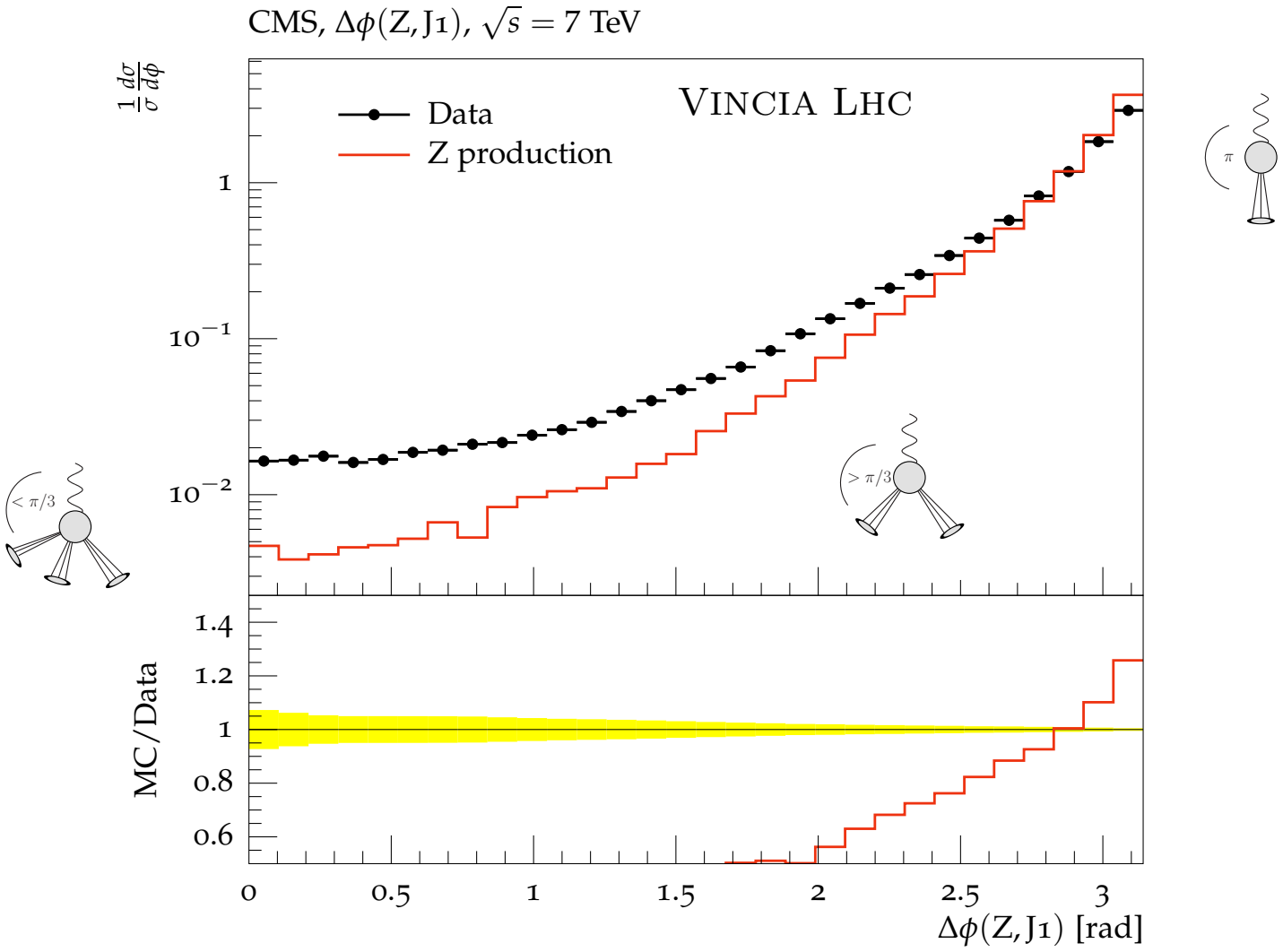
Soft limit needs correlated emissions
Not all subleading soft terms stem from two-particle interference.
ME+PS shower improvements use time-consuming two-step scheme.

FERMILAB idea: Use full LO ME as **multipole** evolution kernel.
Benefit: Shower produces correct LO dynamics – very efficiently.

VIRTUAL NUMERICAL COLLIDER with INTERLEAVED ANTENNAS
Now also available for LHC pheno!

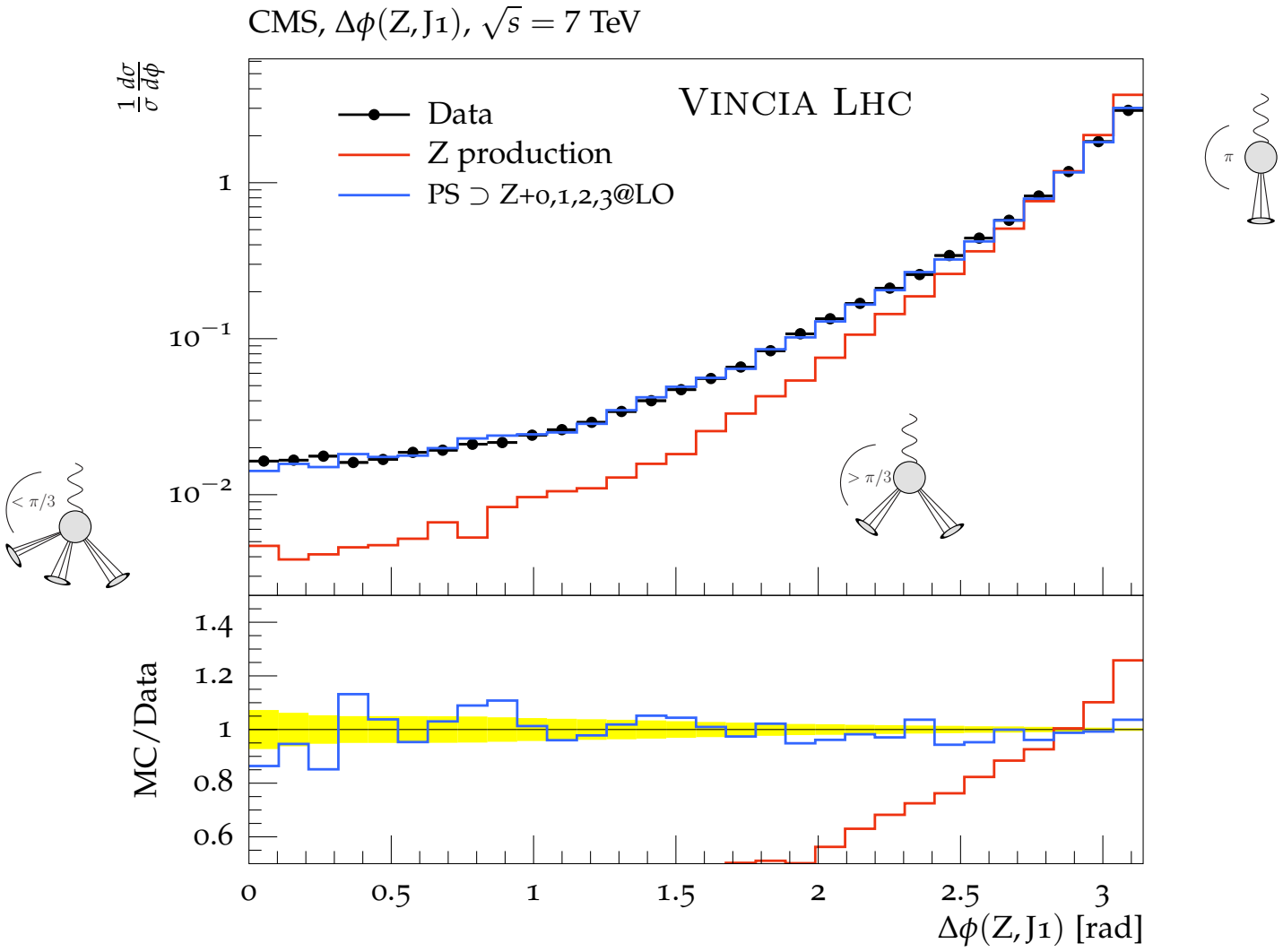
VINCIA preliminary results

[in preparation (Skands, Fischer, Ritzmann, SP)]



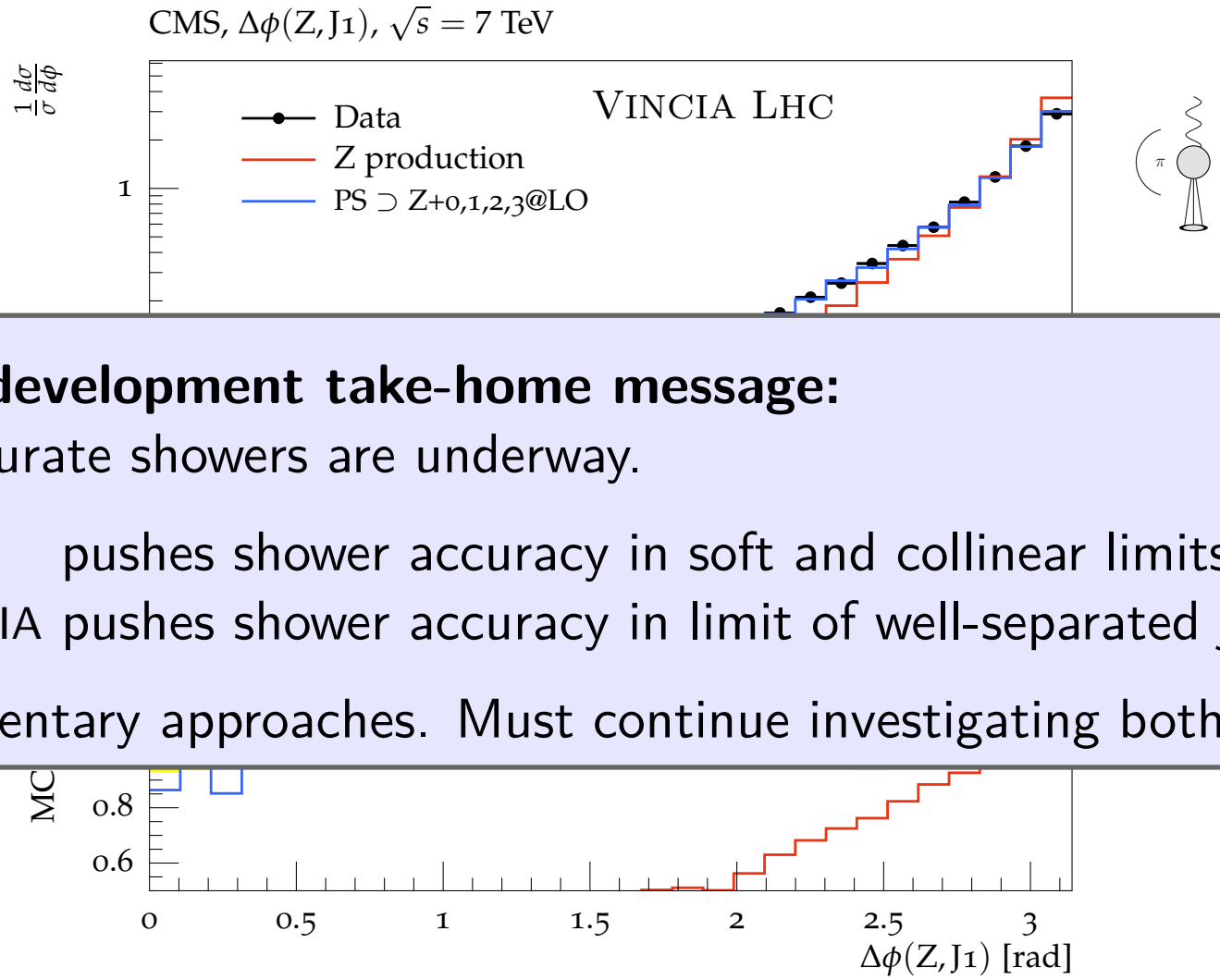
VINCIA preliminary results

In preparation (Skands, Fischer, Ritzmann, SP)



VINCIA preliminary results

In preparation (Skands, Fischer, Ritzmann, SP)



Shower development take-home message:
More accurate showers are underway.

DIRE pushes shower accuracy in soft and collinear limits.
VINCIA pushes shower accuracy in limit of well-separated jets.

Complementary approaches. Must continue investigating both.

Summary and outlook

- The hunt for new physics at high-energy particle colliders requires very accurate simulations of scattering events.
- A good understanding of the Standard Model, and in particular of its perturbative approximation, are crucial.
- Two ways to organise the perturbative expansion:
  Fixed-order calculations and all-order parton showers.
- **Both need to be as accurate as possible.**
- Combinations give a good description of most of LHC data.

Summary and outlook

- The hunt for new physics at high-energy particle colliders requires very accurate simulations of scattering events.
- A good understanding of the Standard Model, and in particular of its perturbative approximation, are crucial.
- Two ways to organise the perturbative expansion:
  Fixed-order calculations and all-order parton showers.
- **Both need to be as accurate as possible.**
- Combinations give a good description of most of LHC data.

But there's much more to life, and the fun has just started.

And there is a lot more to do:
NNLO, NLL, BSM showers, low-W^2 physics, non-perturbative physics...

Let's do next generation event generation!